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INTERNATIONAL MEDICAL MONOGRAPHS

General Editors { DR. LEONARD HILL, F.R.S.
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THE MECHANICAL FACTORS OF DIGESTION

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ILLUSTRATED

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15/7/12

LONDON
EDWARD ARNOLD
NEW YORK : LONGMANS, GREEN & CO.
1911

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TO THE MEMORY OF

PROFESSOR HENRY PICKERING BOWDITCH

IS GRATEFULLY DEDICATED

THIS ACCOUNT OF RESEARCHES BEGUN

UNDER HIS INSPIRATION

GENERAL EDITORS' PREFACE

THE Editors hope to issue in this series of International Medical Monographs contributions to the domain of the Medical Sciences on subjects of immediate interest, made by first-hand authorities who have been engaged in extending the confines of knowledge. Readers who seek to follow the rapid progress made in some new phase of investigation will find herein accurate information acquired from the consultation of the leading authorities of Europe and America, and illuminated by the researches and considered opinions of the authors.

Amidst the press and rush of modern research, and the multitude of papers published in many tongues, it is necessary to find men of proved merit and ripe experience who will winnow the wheat from the chaff, and give us the present knowledge of their own subjects in a duly balanced, concise, and accurate form. In this the first volume of the series Professor Cannon deals with the Mechanical Factors of Digestion. Professor Cannon initiated the method of studying the movements of the bowels by means of the Röntgen rays, and all subsequent researches have been based on his discoveries. We confidently expect that this valuable monograph, containing the fruit of many years' work, will prove of the greatest interest and help to those seeking to understand a subject which is of the first importance in Practical Medicine.

LEONARD HILL,
WILLIAM BULLOCH.

October, 1911.

PREFACE

Researches conducted by the writer and his collaborators in the Physiological Laboratory of Harvard University during the past ten years form the basis of this book. In describing these researches, the related work of other investigators has also been incorporated, and although the exposition of the subject is not intended to be encyclopedic, the whole presents an account of the mechanical activities of the alimentary canal as they are now known and understood. The plan here followed runs the risk of emphasizing unduly a single series of investigations; but, on the other hand, it has the advantage of offering mainly direct testimony rather than secondary interpretation.

Most of the original accounts of the experiments in the Harvard Physiological Laboratory have appeared in American journals devoted to the medical sciences. Much of the material which now appears in Chapters XIV. and XV. has not previously been published, except in brief notes in the *Proceedings of the American Physiological Society*.

The hope of everyone who has tried to extend the boundaries of knowledge is that others will soon take up the work where he has dropped it; and if this book should by chance stimulate further investigation, its most cherished object will have been attained.

WALTER B. CANNON.

Boston, Massachusetts,
July, 1911.

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THE MECHANICAL FACTORS OF DIGESTION

CHAPTER I

GENERAL FEATURES OF THE MOVEMENTS OF THE ALIMENTARY CANAL, AND METHODS OF INVESTIGATION

SINCE the digestive tube is an enfolded portion of the body surface, food taken into it is not in the body, but is merely enclosed. The chief functions of digestion are to render the food serviceable, and to give it a consistency suitable for passage through the wall of the tube into the body. The region in which occur the final preparations for entrance of the food into the body is the small intestine. There the enzymes are found that finish the work begun by the enzymes of the mouth and stomach. In the small intestine also the digested material is mainly absorbed. Indeed, this long, narrow portion of the alimentary tract may rightly be regarded as the very centre of digestive and absorptive activity, with a preparatory reservoir, the stomach, containing accumulated food, which it delivers gradually to the small intestine, and with a terminal reservoir, the colon, ready to receive accumulating waste.

The two general factors of digestion, the chemical and the mechanical, which work towards the absorption of the food, are intimately interrelated. Although our consideration of the activities of the canal will lay emphasis on the mechanical factors, we must not fail to keep in mind the chemical agencies which they accompany and with which they co-operate. The mechanical factors have the functions of mixing the food with the secretions poured out upon it, of exposing the digested food to the absorptive wall, of propelling the food from one region of digestion or absorption to another, and finally of discharging the waste. These functions are of great import to the body, for the

food, if conducted too slowly along the tube, may suffer harmful decomposition; and if forced on too rapidly, it will fail to be properly digested, and will in large measure be lost. We may expect to find, therefore, that the rate of passage through the different parts of the tube is nicely adapted to the speed of the chemical changes.

The neuro-muscular structures by which the mechanical functions of digestion are performed are singularly uniform throughout the tube. They consist of two muscular coats—the circular coat nearer the lumen of the tube, and the outer longitudinal coat. The latter may be lacking in small areas, especially in the region of the stomach. Between these two muscular layers is a primitive nerve plexus—Auerbach's—or the myenteric plexus. At the beginning of the tube, and at its end, striped muscle prevails, but except at these extremities the musculature is of the smooth variety. Smooth muscle is characterized by the relative slowness and the rhythmicity of its contractions, and by its ability to exhibit rhythmic activities at various levels of sustained shortening, or tonus. The great importance of these characteristics will appear as we consider further the functions that are performed by this smooth muscle and its nerve plexus.

In accordance with uniformity of neuro-muscular structure, the canal presents uniformity of mechanical action. In the course of digestion the food is subjected to an orderly series of sequentially related processes; what occurs in an advanced region is more or less dependent on what has occurred in a region previously traversed. The food, therefore, must be moved always onward. The continued progress of the food is accomplished in the main by peristaltic waves—rings of constriction which sweep slowly along limited extents of the canal. These waves are an expression of the neuro-muscular arrangements in the wall. Although, as we shall see, the peristalsis of the stomach and proximal colon is somewhat different from that of the small intestine, we need not restrict the term to any particular region. In all parts of the canal, therefore, peristalsis is the most characteristic mechanical activity that affects the digestive processes.

The manner in which peristalsis operates varies in different parts. Where digestive juices are lacking and absorption does not occur, as in the œsophagus, the waves press the food onward

with rapidity. On the other hand, where digestion and absorption can take place, rapid progression is prevented by sphincters; and the recurring peristaltic waves passing over the food toward closed sphincters serve to mix the food with the digestive juices, as in the stomach, or to expose the food to the absorbing mucosa, as in the ascending colon. In the long course of the small intestine, where there are no sphincters to oppose peristalsis, peristaltic activity is less noteworthy than in the other regions, and the mixing and churning functions are performed by a special method—the rhythmic contraction of the circular fibres which knead the intestinal contents without causing any considerable progression. The advancement of the contents in the small intestine, however, is effected by the peristaltic wave. In all regions of the digestive tube, therefore, this wave is to be seen as the means of conveyance.

The muscles at the beginning and at the end of the canal are under voluntary control. Thus we can determine what food shall be taken into the tube, and when, and we can, within limits, govern the discharge from the tube. The great mid-region, however, is normally automatic, and free from voluntary interference. The active stomach, for example, can be removed from the body and placed in a moist chamber, where its contractions will continue for an hour or more. These automatic structures are, nevertheless, subject to influences from the central nervous system which augment or diminish their inherent activity. The important relations which exist between the alimentary tract and the central nervous system have only recently been ascertained, as new methods of research have brought forth the clear evidence. We shall see that disturbances arise if the extrinsic innervation is removed, and that disturbances may arise also because the extrinsic innervation is present.

The sensitiveness of the alimentary canal to operative interference has been the chief difficulty in past investigations of the digestive process. The stomach and intestines, energetically active during the height of digestion, are prone to cease their activities suddenly when the abdomen is opened, a striking change, likened by Meltzer to the hush that falls upon a company when a stranger appears at the door. Of course, under these circumstances the normal movements of the canal cannot be studied. The famous physiologist, Johannes Müller, testified that he had never seen clearly the peristaltic movements of the

stomach. For centuries the priests and the butchers, who watched the entrails of their sacrificed victims, knew as much as the physicians about the mechanical factors of digestion. Only as methods were devised which maintained more or less perfectly the normal conditions of the digestive organs were the natural activities slowly ascertained.

Among the methods employed to preserve so far as possible, or to simulate during investigation, the usual surroundings of the alimentary canal, the fistula is the oldest. Through an opening between the lumen of the canal and the body surface, registering apparatus has been introduced which indicated the movements of the region. Fistulas made at different distances along the tube have also been used to study the rate of advancement of the food and the degree of its alteration as it passed from one stage to another in digestion. At best, however, the fistula permits only an inferential judgment of the mechanical agencies at work in a narrowly localized portion of the canal, a portion, furthermore, which may be disturbed by the adhesions due to operation.

Less disturbing than the fistula method is the direct introduction of registering apparatus through the mouth. Thus the time relations of changes of pressure in the pharynx, the œsophagus, and the two ends of the stomach, have been obtained, and conclusions have been drawn as to the activities that produced the pressures.

A method giving more direct information than either of the foregoing methods is that introduced by v. Braam-Houckgeest,[1] which consisted in opening the abdominal cavity of the anæsthetized animal in a bath of physiological salt solution at body temperature. If the temperature of the solution is sustained and active digestion is in process, the normal movements of the stomach and intestines can be directly observed. The method involves such serious operative interference, however, that with some animals (*e.g.*, the rabbit[2]) the usual gastric peristalsis suffers profound and lasting nhibition. The effects of the movements on the food, and the rate at which the food is advanced, cannot be readily ascertained in the salt bath.

All physiological processes observed under conditions rendered unnatural by the exigencies of the method employed must be subject to standardization by the results of studies made under more natural conditions. None of the methods above described

preserve strictly the normal state of an animal digesting its food in its usual manner. When the X rays were discovered, a new means of investigating the alimentary tract was provided, which permitted observations to be made without interfering with the animal to any disturbing degree. This means of research was suggested to me, when a medical student, by my teacher of physiology, Professor H. P. Bowditch, in the autumn of 1896. The results obtained by use of the X rays prove that, in order to reveal the natural activities of the digestive organs, the older methods must be used with extreme care. When such care is exercised, however, those methods can be safely employed to confirm and supplement the X-ray observations. Most of the data which will be hereafter presented have been secured by study of the deeply hidden alimentary canal by means of the X rays.

The method consisted in giving animals food thoroughly mixed with subnitrate of bismuth,* and observing the shadows cast by the X rays on a fluorescent screen. Thus the dense bismuth powder, uniformly mixed with the food that fills the stomach, throws the dark shadow of the stomach contents on the screen, and the changes in the shape of the outline reveal the movements of the organ. That the addition of bismuth subnitrate to the food produces no peculiar effects on the movements has been proved by finding no noteworthy differences when other heavy salts, as, for example, barium sulphate, is mixed with the food.[3] Clinical studies on man by Schule also indicate that subnitrate of bismuth in the food does not interfere with normal gastric motility,[4] and observations by Cook and Schlesinger show that bismuth oxychloride passes through the digestive tube at the rate of charcoal.[5]

The animal most commonly used in the laboratory investigations was the cat. Confirmatory observations, however, have been made on the dog, rabbit, guinea-pig, white rat, and on man. For studying the conditions in the cat, deprivation of food for twenty-four or thirty hours previous to the feeding was usually necessary, in order to make certain that the digestive

* A few of the animals unaccountably died after being observed. Cases of death or severe poisoning in man after the administration of large doses of subnitrate of bismuth have been reported in Germany and the United States. As the subnitrate of bismuth may to some extent be chemically changed in the stomach, Hertz has advocated the use of bismuth oxychloride, which is unaffected by either the gastric or the intestinal juices. (See Hertz, *Constipation and Allied Intestinal Disorders*, London, 1909, p. 335.)

tube was empty. A dose of castor-oil, administered about twelve hours before the feeding, gave still further assurance that only the digestion of food mixed with the bismuth salt would be observed. The animals were either permitted to eat voluntarily from a dish, or were placed on the animal-holder and fed from a spoon, usually with little or no difficulty. The amount of food given varied between 25 and 50 c.c., except where uniform amounts were given for special purposes. One or two grammes of the bismuth powder produced a dim shadow of the stomach within which could be clearly seen the darker forms of any food containing a larger amount of the substance. Four or five grammes, mixed with 25 c.c. of food, were needed to see the passage of the food from the pylorus.

The animal-holder consisted of a framework supporting a sheet of black rubber cloth. The frame was made of two side-pieces, each 80 centimetres long and 2·5 centimetres square, connected at either end by blocks 2·5 centimetres thick, 12·5 centimetres wide, and 16 centimetres long. The rubber cloth, which sagged for the comfort of the animal, was fastened by strips of wood to the inner surface of the frame. Through the side-pieces were holes 0·6 centimetre in diameter, and 5 centimetres apart. The legs of the animal were secured by leather nooses ; the leather passed down through one of these holes and up through another, in which it was made fast by forcing a pointed peg into the hole with it. The cat's head was held by two adjustable pegs, one on either side of the neck, which were connected above. The advantage of this holder lay in its comfortableness for the animal, and in the ease of feeding which it permitted in case artificial administration of food became necessary.

For seeing the regular movements of the stomach, the animal was tied back downward, with the fore-paws in nooses at either side, and the hind-legs stretched out and fastened to the holder in such manner as to permit the body to lie slightly turned towards the right side. This position was also favourable for watching the course of food through the œsophagus. The movements of food in the intestines could be readily observed with the animal lying directly on the back. Female cats lay on the holder sometimes for periods of an hour or more without making attempts to break away or manifesting signs of discomfort. In marked contrast was the behaviour of the male cats ; almost without exception they showed signs of anxiety

or rage when fastened down. The important effects on digestion arising from these different ways of reacting to the novel surroundings will be described later.

The animal-holder was supported on a leaden surface in which a hole was cut only sufficiently large to permit the body of the animal to be illuminated by the X rays. Below the holder, at a distance of 30 centimetres between the anode and the animal, was placed the tube generating the rays. The tube was so surrounded by lead that none of the rays could reach the observer. The observations were conducted in a dark room. All light from the tube and from the machine which generated the electric discharge was shut off from the observer by drapings of black cloth. Thus in an open fluorescent screen placed on the animal's belly, the shadows could be observed simultaneously by more than one person. Over the screen was fastened a layer of lead glass. On transparent tissue paper laid over the glass the outlines of the gastric and intestinal contents could be traced, and thus records of the conditions at various times in the course of digestion could be preserved. In case of doubt as to the accuracy of the tracings, an electric light momentarily flashed on the tracing before the tissue paper was removed from the screen permitted the outlines drawn on the paper to be compared with the shadows, and the records thus verified.

By use of the X rays the rate of passage of food through the œsophagus, the speed of gastric peristalsis and its rhythm, the oscillating contractions of the small intestine, the peculiar antiperistalsis of the large intestine, the rapidity of discharge of gastric contents into the duodenum, the time required for material to be carried to the colon, and all the influences external and internal that affect these processes, can be observed continuously for as long a time as the animal remains in a state of peace and contentment. The results of these observations we shall now begin to consider.

REFERENCES.

[1] v. Braam-Houckgeest, *Arch. f. d. Ges. Physiol.*, 1872, vi., p. 263.
[2] See Auer, *Am. J. Physiol.*, 1907, xviii., p. 359.
[3] Cannon, *Am. J. Physiol.*, 1904, xii., p. 388.
[4] Schule, *Ztschr. f. Klin. Med.*, 1896, xxix., p. 67.
[5] Hertz, *loc. cit.*, p. 335.

CHAPTER II

THE MOVEMENTS OF MASTICATION AND DEGLUTITION

The Movements of Mastication.

The freedom of movement of the lower jaw permits a wide variety of relations between the upper and lower rows of teeth. They can be brought together, separated, or pressed with a sliding motion one row upon the other either forward and backward or from side to side. The up and down motion is essential to the use of the biting front-teeth; the side to side motion is more useful in the later process of chewing. The tongue and cheeks act like the hopper of a mill, and force the food between the grinding facets until it is broken or torn into fragments of proper size for swallowing.

The duration of mastication varies with appetite, with age, the demands of business, the quantity of food in the mouth, and especially with the nature of the food—whether fluid or gummy, moist or dry, crisp or tough. The amount of mastication given any food is related to the readiness with which a mass is comminuted, insalivated and gathered into a bolus, and is not related to the degree of salivary digestion. Thus soft, starchy food is little chewed, whereas hard or dry food, not starchy in nature, may require much chewing before ready to be swallowed.[1]

The effect of the mechanical treatment in the mouth is the production of a semi-fluid mush in which there are likely to be particles of varying size. Lehmann has reported that when he chewed different substances, such as beef, macaroni, potato, and raw apple, until the impulse to swallow came, some of the substance was already in solution; and of the rest, by far the larger amount was reduced to particles less than 2 millimetres in diameter.[2] Such comminution must result in an enormous

increase in the surface exposed to the action of digestive enzymes, and thereby promotes the rapidity of their action. The observations of Lehmann have been confirmed by Fermi and by Gaudenz. In the mushy mass, however, Gaudenz found[3] particles over 7 millimetres in diameter, and he states that the largest normally swallowed do not exceed a diameter of 12 millimetres. For determining the proper grade of fineness of the food, the tongue, the teeth, the gums and cheeks, make the needed investigation. If some particles in the bolus as it is carried backward in the mouth are too large, they are returned for further mastication.

The secretion of saliva, which softens the hard particles in the food, and with its ptyalin starts the digestion of starches, is also promoted by the movements of mastication. According to Gaudenz,[4] the weight of the material in the mouth when ready to be swallowed varies in man between 3·2 and 6·5 grammes, and of this, if the food has been chewed for twenty or thirty seconds, 1 or 1·5 grammes may be saliva.

The mass suitable for normal mastication has an average volume of about 5 c.c. Not all animals chew the food as finely as man commonly chews it. The dog and cat swallow pieces of meat so large that apparently the œsophagus must have difficulty in conveying them, and yet these animals seem to have no instinct to divide this food into smaller and more readily manipulated fragments. The large lumps are merely moved about in the mouth until they are coated with saliva, and are then forced backward into the gullet. In man, also, food may be swallowed in such haste that it is barely covered with the saliva which usually lubricates the passage through the œsophagus. Masses 10 or 12 millimetres in diameter may thus enter the stomach with little evidence that the teeth have in any way affected them. The ability to bolt food in unbroken masses can doubtless be cultivated ; and a person who has made himself an expert in this act can probably push downward bigger masses than those just mentioned.

The pressure exerted in the process of mastication may be surprisingly great. The pressure which the molars, for example, are capable of exerting, as determined by a spring dynamometer, may be as high as 270 pounds.[5] With a direct thrust the crushing-point of cooked meats has been found to vary between 15 and 80 pounds ; of candies, between 30 and 110 pounds ; and of various kinds of nuts, between 55 and 170 pounds. The figures

for meats may be considerably less if the jaws grind from side to side. The teeth then bite through cooked tongue when the pressure is only 1 or 2 pounds, and through tough round of beef when the pressure is about 40 pounds. Saliva is a further aid to mastication if starchy food is being chewed. Thus soft bread is not bitten through even with 60 pounds direct pressure, but hardens to a solid mass. If the bread is softened with a little saliva, it is easily masticated with a pressure of 3 pounds.[6] Before the saliva is well mixed with the food, however, the high pressure may have to be applied a large number of times to reduce the mass to bits.

Breaking the food into fine fragments and mixing it thoroughly with saliva, so that it might be sufficiently moist to be swallowed, were formerly regarded as the most important results of mastication. Recent researches have revealed less obvious results. The voluntary act of chewing has been found to have much significance for the proper initiation of gastric digestion. During mastication substances of pleasant taste are brought in contact with the gustatory organs of the tongue and cheeks, and odours released from the separated food rise to the olfactory region of the nose, and through the pleasurable sensations aroused by these stimulations the gastric juice is reflexly started flowing, in preparation for gastric digestion.[7] Not only in laboratory animals, but also in human beings, this remote effect of pleasurable sensation in the taking of the food has been demonstrated. Hornborg and others have reported cases of gastric fistula in children, in whom an active secretion of gastric juice was observed when agreeable food was chewed, whereas the chewing of indifferent material was without influence.[8] As has been proved by the experiments of Pawlow and Edkins, this initial " psychic juice " may be a prime condition for continuance of gastric secretion. We shall see that it may also be the prime condition for the co-ordination of gastric and intestinal digestive proceses.

Still another remote effect which may result from the chewing of agreeable food is the development in the stomach of a condition of tonic contraction, a state of sustained shortening of the circular muscles which nicely adapts the capacity of the organ to the contents, whatever the amount swallowed. The peristalsis of the stomach, which churns the food with the gastric juice and pushes the chyme onward into the duodenum, is

dependent on the tension developed in the muscular wall as a result of its tonic state.

Although these secretory and motor activities of the stomach are not, as we are aware, directly subject to voluntary control, they are capable of being profoundly influenced, favourably or unfavourably, by the character of the experiences, agreeable or disagreeable, that attend the process of mastication. And these experiences we can to some extent determine for ourselves.

The Movements of Deglutition.

The movements of deglutition, in common with many other physiological processes, were explained by the older physiologists on anatomical grounds. Thus, Magendie[9] divided the act into three parts, corresponding to the anatomical regions of the mouth, pharynx, and œsophagus. The muscles of each of these divisions were regarded as the active agents in propelling the food onward.

The function of moving the mass to the pharynx was variously ascribed to the tongue itself, to the mylo-hyoid muscles swung beneath the tongue, and to gravity. For the action of the second part, the movements of the pharynx, there was more unanimity of opinion, since the constrictors, especially the middle and lower, were evidently concerned. The passage of a swallowed mass along the œsophagus was, until 1880, ascribed solely to peristalsis. In that year, Falk and Kronecker,[10] who had studied the movements of the mouth and pharynx in deglutition, advanced the theory that the act is accomplished by the rapid contraction of the muscles of the mouth, and that œsophageal peristalsis is of secondary importance.

The sudden discharge involved in Falk and Kronecker's theory requires the temporary closure of all the exits from the mouth except that into the œsophagus. That there is such a closure anyone can observe to some extent in himself. When the food has been sufficiently masticated, it is gathered in a depression on the dorsum of the tongue, in readiness for swallowing. The tip and sides of the tongue, pressed against the teeth and hard palate, shut off the possibility of escape forward and laterally—we can swallow with the mouth open, but not with the tongue relaxed. Since the paths of respiration and deglutition cross just above the larynx, respiration is now reflexly

stopped. A quick contraction of the mylo-hyoid muscles suddenly presses the tongue upward against the hard palate, and by a contraction of the hyo-glossus the organ is drawn backwards. At the same time, by action of the palato-pharyngeus muscles, which form the posterior pillars of the fauces, the pharynx is drawn to a narrow cleft, and against this narrow opening the soft palate is pulled by contraction of the levator palati.[11] Thus exit into the naso-pharynx is prevented.

Now, as the tongue rises and slips inward, it acts as a piston, and drives the bolus first against the downward-sloping soft palate, next against the back wall of the pharynx, then on between the pharyngeal wall and the posterior surface of the epiglottis, the tip of which lies in contact with the tongue's base.[12] Thus far the top of the œsophagus has been kept closed by pressure of the larynx against it. Immediately the hyoid bone and the larynx are lifted and brought together, and the epiglottis is pressed back till it shuts the laryngeal aperture. As soon as the hyoid and larynx are lifted they are pulled forward, and thus the œsophagus is opened. Meanwhile the tip of the epiglottis slips downward along the back wall of the pharynx, pushing the bolus, probably with a final quick impulse, into the gullet. Then all the structures return to their resting positions. Of course, this sequence of movements occurs with precipitate suddenness, and can be known only by most careful analysis.

Falk and Kronecker found that during the initiation of the act of swallowing the closed buccal cavity showed a manometric pressure of 20 centimetres of water. They found that the same pressure appeared also in the œsophagus, but not in the stomach. The pressure developed in the mouth was considered sufficient, therefore, to force food quite through the œsophagus without the aid of peristalsis. Confirmatory evidence for the theory that the descent to the stomach is rapid was found in the common experience that cold water can be felt in the epigastric region almost immediately after being swallowed. And, further, autopsies have shown that, when strong acids pass through the gullet, they corrode areas only here and there, and not the entire mucous membrane, as would be the case were the acid pressed slowly to the stomach by peristalsis.

During the same year, in confirmation of the above results,

the well-known experiments of Kronecker and Meltzer[13] were reported. A rubber balloon, connected by a tube to a recording tambour, was placed in the pharynx, and another balloon, similarly connected, was introduced a varying distance into the œsophagus. When water was swallowed, the increased pressure on the pharyngeal balloon was instantly transmitted to the first tambour, which recorded a rising curve on a rotating drum. Almost immediately thereafter the œsophageal balloon was compressed, and its tambour recorded a curve below the first. After a varying number of seconds, according to the distance below the pharynx at which the balloon was placed, a second rise of pressure in the œsophagus was registered. The first indication of increased œsophageal pressure was explained as due to the sudden discharge of food past the balloon ; the second curve was explained as due to a peristaltic wave which swept more slowly along the tube.

To demonstrate that the first rise of pressure registered from the œsophagus resulted from the rapid squirting of liquid from the mouth, Meltzer devised another experiment. A strip of blue litmus-paper was placed opposite the side openings at the lower end of a stomach-tube. Attached to the paper was a thread which ran through the tube to the upper end. The tube was now passed into the lower end of the œsophagus, and an acid drink swallowed. If only a half-second elapsed after the beginning of deglutition, the litmus-paper, when pulled away from the side openings, was found reddened by the acid.

From these observations, Kronecker and Meltzer concluded that liquids and semi-solids are not conveyed down the œsophagus by peristalsis, but are forcibly squirted into the stomach, by the rapid contraction of the muscles of the mouth, before the muscles of the pharynx or the œsophagus have had time to contract. For this purpose the mylo-hyoids alone are sufficient, since the middle and inferior constrictors of the pharynx can be sectioned without in the least interfering with the act. Indeed, Meltzer has recently shown[14] that the musculature of the entire cervical œsophagus can be wholly removed from a dog, and that the animal thereafter is able to drink milk and water quite normally even when the bowl is placed on the floor, and the fluid must be forced into the thoracic œsophagus against gravity. If the function of swallowing can thus be performed by the

pressure developed in the mouth, the succeeding peristaltic wave is of use merely to gather any fragments that may have adhered to the wall in the rush of food through the œsophagus, and to carry this meagre load to the stomach.

According to Kronecker and Meltzer,[15] the human œsophagus may be divided functionally into three parts: a cervical part 6 centimetres long, a middle part 10 centimetres long, and the lowest part of uncertain length. These three parts contract in succession, 1·2, 3 and 6 seconds respectively, after deglutition begins; but each part, according to Meltzer, contracts as a unit, simultaneously throughout its length. The duration of the contraction is more prolonged in the lower thoracic section than in the upper thoracic or the cervical section. The human œsophagus, according to this view, would undergo three progressive sectional contractions not peristaltic in nature.

To determine whether the cardiac sphincter offered any resistance to a rapid passage of food into the stomach, Meltzer made use of another method.[16] If a stethoscope is placed over the epigastrium during the swallowing of liquids, a sound can be heard six or seven seconds after the rise of the larynx. The sound is ascribed to the passage of the swallowed mass, liquid, and air, through the tonically contracted cardia. In a few cases a sound is heard immediately after swallowing, a result which has been explained as probably due to insufficiency of the cardia.* These phenomena led Kronecker and Meltzer to modify their previous views. They now maintained that the swallowed mass is not squirted directly into the stomach, but is checked a short distance above the cardia. There it remains until overtaken by the succeeding peristaltic wave, about six or seven seconds later, when it is pressed onward into the stomach.

The methods employed in these carefully-conducted experiments were possible sources of error. The presence of one or more balloons and a stomach-tube in the œsophagus may properly be regarded as disturbing to normal deglutition. What *can* be done by the organism, while compensating for disturbing experimental conditions, may not be the normal action of the

* Hertz has suggested (*Brit. M. J.*, 1908, i., p. 132) that the first sound is caused by the impact of fluid against the posterior pharyngeal wall, for it is louder in the prone than in the supine position. Since it can invariably be heard in the neck region, it seems not to fit the occasional character which Meltzer gave it. The second sound, Hertz states, is like a trickle in the upright and like a squirt in the horizontal posture. It corresponds to the final disappearance of the swallowed mass into the stomach.

same organism in a more natural state. Furthermore, although Kronecker and Meltzer themselves declared that their results were true for liquids and semi-solids only, and admitted that a dry bolus could not be shot down the gullet, yet the use of the terms "liquid," "swallowed mass," and "bolus," easily leads to the inference that their results are true for the swallowing of food of all consistencies.

With the purpose of studying the rate of movement of solids, semi-solids, and liquids, in the normal œsophagus, Mr. A. Moser and I undertook, in the autumn of 1897, observations on various animals by means of the X rays. Thus anæsthesia could be dispensed with, no operative interference would be required, only the food itself would be present in the gullet; in short, the animal could swallow its food under quite natural conditions.

Observations were made on the long neck of the goose, on the cat, dog, horse, and man. In watching the process of swallowing in the goose, the neck of the animal was extended by a tall pasteboard collar, which in no way compressed the gullet. A bolus of corn-meal mush placed in the pharynx was seen to descend slowly and regularly. About twelve seconds elapsed while the bolus was moving through 15 centimetres of the œsophagus. Careful records indicated a slight slowing of the movement as the bolus descended. A syrup which, when mixed with bismuth subnitrate, still dropped quickly from the end of a glass rod was used as a liquid mass. This liquid, fed through a pipette, also passed slowly and regularly down the œsophagus, clearly by peristalsis. The rate was about the same as for solid food. In the bird, therefore, peristalsis is the only movement, without regard to the consistency of the food. The quick propulsion of liquids from the mouth does not occur. In the absence of this action a greater reliance on gravity is observed. As the mouth is filled the head is raised, and the fluid, after trickling into the œsophagus, is carried onward by peristalsis. It is of interest to note that, when the mylo-hyoid muscles are paralyzed in a mammal, the animal raises the head in swallowing, after the manner of birds.

In observations on the cat and dog, gelatine capsules containing the bismuth powder or shreds of meat wrapped about it were used as more or less "solid" food. For soft solids a mush of bread and milk was selected, so fluid as to be easily drawn up into a large-bore pipette, and yet so viscid as to retain the

bismuth powder in suspension for a long period. After trying a number of other methods, we finally decided that a simple mixture of milk and bismuth subnitrate, shaken in a test-tube and immediately drawn into a pipette, was the most satisfactory means of supplying a liquid mass.

Solid food passed down the entire œsophagus of the cat and dog by peristalsis. In the cat the rate was uniform to the level of the heart; about four seconds were required for the passage. In the lower section, from the heart to the stomach, the rate was distinctly slower. The distance was less than one-third the entire canal, yet the time spent in this part was six or seven seconds, or three-fifths of the entire time of the descent. In the dog the solid bolus was quickly discharged into the œsophagus, and descended rapidly for a few centimetres, sometimes nearly to the base of the neck. Thereafter the rapidity was diminished; yet no pause was observed—the bolus simply moved more slowly. Unlike the cat there was no slackening of speed below the level of the heart, and without change of rate, therefore, the mass was passed into the stomach. Four or five seconds were required for the descent from larynx to cardia.

Semi-solids were carried in the dog and cat much as the solids were carried. The only difference observed was a slightly more rapid passage along the upper œsophagus in the cat. Liquids were forced into the tube at a more rapid rate than the solids and semi-solids. In the cat only 1·5 or 2 seconds were required for the liquid to pass from the laryngeal to the mid-heart level.[17] Then, after a pause which lasted from a few seconds to a minute or more, the œsophagus apparently contracted above the liquid, and pushed it slowly into the stomach. Sometimes the peristaltic wave seemed to be started by a swallowing movement, though the exact course of the contraction could not, naturally, be directly observed. In the dog, liquids were evidently squirted for some distance along the œsophageal tube. To free the tube from any disturbing tension or compression, the head of the animal was released from the holder and held in the hands. Sometimes the liquid descended rapidly as far as the heart, at other times no farther than the base of the neck. Without a pause it then passed on with perfect regularity and entered the stomach. Meltzer has reported direct observations of the œsophagus of the anæsthetized dog, and states that swallowed liquids are projected rapidly a varying distance along the tube,

the distance depending on the quantity swallowed, the force of the swallowing movement and the degree of contraction of the lower œsophagus.[18] When the liquid ceased its rapid flight, instead of being promptly moved onwards, Meltzer states that it suffered a considerable delay before a peristaltic wave arrived and forced it along. This discrepancy between Meltzer's and our observations was probably due to anæsthesia, which is known to interfere greatly with œsophageal peristalsis; for Meltzer has since reported that objects present in the thoracic œsophagus of the unanæsthetized dog are at once carried into the stomach without the aid of any peristaltic wave started by the act of swallowing.[19] This peristalsis of local origin, which Meltzer has denominated "secondary peristalsis," would account for the continuous progress of a swallowed bolus even when it has been projected deep into the œsophagus by the forceful movements of the mouth.

The influence of consistency of food was further demonstrated in a very simple way by our observations on the horse. A bolus made from masticated hay or grain can be seen or felt passing along the horse's œsophagus at the rate of 35 or 40 centimetres per second. Even a mixture of bran and water, thin enough to run easily through the fingers, was not carried faster than the hay or grain. But liquids were shot along the gullet much too rapidly to be accounted for by any peristaltic activity. Anyone who will place his hand under the lower jaw of the horse while the animal is drinking will find in the energetic contraction of the mylo-hyoids a sufficient explanation of the rapid passage of water through the œsophagus. The rate is more than five times as rapid as that of solids and semi-solids.

X-ray observations of deglutition in the human being revealed the same conditions that we found in the horse. Gelatine capsules were seen descending steadily and regularly at a relatively slow rate from the region of the pharynx to a point below the heart. A semi-solid consisting of a mush of bread and milk was traced over the same course, and it had nearly the same rate of progression as the solid. In both cases the swallowed material was evidently pushed onward by peristalsis. The X-ray observations of Lossen on persons who swallowed potato soup confirm our conclusion that the passage of semi-solids through the œsophagus is not sudden.[20]

According to the X-ray studies of Hertz, solids pass along the human œsophagus slowly, no matter what the position of the

body; the time required when the solids are well lubricated varies between eight and eighteen seconds, but a dry bolus may remain above the cardia many minutes.[21]

We found no evidence of the contraction of the œsophagus in three sections, as Kronecker and Meltzer reported. If the œsophagus contracts in sections, with an interval of two or three seconds between the contraction of adjoining sections, we should expect a checking of the progress of the swallowed mass at each stage. The steady progress of the bolus, as we observed it, does not harmonize with the view that successive long stretches of the œsophagus undergo each a single contraction simultaneously throughout its length. Schreiber,[22] who has studied the contractions of the human œsophagus with the method used by Kronecker and Meltzer, was also unable to find a separation of the tube into three sections, each with its own time for contraction. Instead, his curves revealed the existence of a constriction registered gradually later as the recording apparatus was placed gradually deeper in the œsophagus. This moving constriction can be explained only as a peristaltic wave. As in our observations on the cat, Schreiber found in man that peristalsis was rapid in the upper œsophagus, and much slower in the thoracic portion.

Although Schreiber showed that the first rise in Kronecker and Meltzer's records could be obtained when the œsophagus above the recording balloon was closed, or when the swallow was "empty," the possibility of rapid passage of a bolus through the œsophagus was not thereby excluded.

Our X-ray observations on the swallowing of liquids in the human being are quite in accord with Kronecker and Meltzer's contention. Water holding bismuth subnitrate in suspension was drunk by the subject, and at each swallow the liquid was projected rapidly through the pharynx and well down into the thoracic œsophagus before it was lost to view. Hertz was able to trace the passage of bismuth salt suspended in milk all the way to the stomach in fourteen normal persons. After having been "shot rapidly down the greater part of the œsophagus," the fluid was forced slowly into the stomach. Between four and eight seconds were required for the entire process, and of this time about half was spent in going through the cardia. In the head-down position fluids ascended the œsophagus at approximately one-third the rate of descent in the upright position.[23]

Mikulicz became convinced by repeated œsophagoscopic examinations that not only is the resting tube in the thoracic region wide open and filled with air, but that, owing to the elasticity of the lungs, the pressure prevailing is slightly less than atmospheric.[24] Doubtless this condition, if generally present in man, is highly favourable to the projectile passage of liquids from the mouth to the region of the cardia.

We may conclude that the act of swallowing varies in different animals and with different consistencies of food. In various mammals studied by means of the X rays, solid and soft mushy foods were invariably carried down by peristalsis; in the horse and man, liquids were forcibly discharged along the œsophagus by the quick contraction of muscles of the mouth, and even in the dog and cat liquids descended for some distance faster than more viscid masses. Whether liquids invariably descend to the stomach at a rapid rate doubtless depends, as Meltzer has suggested, on the amount swallowed, the force of the swallowing movement, and the degree of contraction of the gullet. Since two of these three factors are under voluntary control, it is quite possible that mammals needing for any reason to propel liquids rapidly through the œsophagus would in that necessity be able to do so.

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CHAPTER III

THE NERVOUS CONTROL OF DEGLUTITION

As the word implies, the œsophageal tube is merely a "food-carrier," serving to transmit nutriment quickly from the first digestive region to the second. The variations in the rate of transmission in different animals and in different parts of the œsophagus of the same animal can be explained by differences in histological structure. Thus the uniform slow peristalsis of the goose is performed by an œsophagus composed entirely of smooth muscle. The change from rapid to slow peristalsis near the heart region in the cat's œsophagus corresponds to a change from striated to smooth muscle in the structure of the wall. The absence of any similar slackening of speed in the lower thoracic region of the dog is accounted for by the absence of the change of structure—the dog's œsophagus is composed of striated muscle throughout. The more rapid contraction of striated muscle compared with smooth muscle gives a reason for the bolus reaching the dog's stomach in four or five seconds, instead of requiring nine seconds or more as in the shorter œsophagus of the cat. The slow contraction of the lower portion of the human œsophagus, noted by Kronecker and Meltzer, and by Schreiber, is explained by the fact that this portion is composed, like the œsophagus of the cat, of smooth muscle.[1] These distinctions are important for our understanding of the action of the œsophagus in relation to its innervation.

The process of swallowing transfers the food from the short region in which it is subject to voluntary control to that extensive region in which the digestive processes are automatically managed without affecting consciousness or being disturbed by whims of the will. Not until the waste from the swallowed food appears at the terminus of the canal does direct voluntary interference again become possible. Indeed, the region at the

start where we can do as we wish with the food is only that concerned with mastication; as soon as swallowing begins, the bolus slips suddenly into the grip of a train of reflexes from which there is normally no recall. Like other reflex mechanisms, the arrangements for swallowing involve afferent paths and efferent paths. The remarkable provisions for efficient action, especially in the œsophageal region, make the innervation of deglutition peculiarly interesting.

The origins of the afferent impulses, which start the series of reflexes, have been studied in different animals; and variations have been found in their locations, just as variations were found in the rate of passage along the œsophagus. The areas at which the impulses can be started have been classified into the most sensitive area or "chief spot" for initiating the swallowing reflex, and accessory spots, of less sensitiveness, from which the reflex is not so readily aroused. According to the careful investigations of Kahn,[2] the chief spot in each animal is found in the natural path from mouth to œsophagus; the accessory spots lie in out-of-the-way places, into which, however, small particles of food may be driven. Thus in the dog and cat the chief spot is an area on the back wall of the pharynx, opposite the posterior opening of the mouth cavity—an area supplied by the glosso-pharyngeus nerve. Accessory spots are present on the upper surface of the soft palate, supplied by the glosso-pharyngeus and the second branch of the trigeminus, and on the dorsal face and base of the epiglottis, supplied by the superior laryngeal nerve. In monkeys the chief spot is in the tonsillar region, and accessory spots appear at the entrance to the larynx, on the back and base of the epiglottis, and on the wall of the pharynx.

These spots were found by touching the mucous membrane of the mouth and pharynx here and there until the reflex occurred. The chief spots are extraordinarily sensitive to mechanical stimulation, and the reflexes which they call into activity are unusually indefatigable. Wassilieff, for example, was able by touching one point in the mucous membrane to evoke in succession fifty acts of deglutition.[3]

Accurate observations on man as to the most sensitive areas for inducing the deglutition reflex have not been made, though in all probability the back wall of the pharynx and areas near the base of the tongue, when touched by foreign bodies, will evoke the movements. The perfect reflex character of deglutition, and

its absolute dependence on incoming impulses from special spots in the mouth and pharynx, was clearly demonstrated by Wassilieff. He swallowed a small sponge moistened with cocaine, and immediately drew the sponge back by means of a thread attached to it. The ability to swallow was for some minutes entirely lost, and the saliva, which was abundantly secreted, had to be expectorated. Just as there must be a sensitive region to be stimulated, so likewise there must be an object to stimulate it. We need only to swallow several times in rapid succession, until no more saliva is present in the mouth, to observe how impossible the act becomes in the absence of a peripheral stimulus. Under normal conditions of ingesting food, the sensitive spot can be stimulated either by liquid buccal contents flowing back upon it, when involuntary swallowing occurs, or by more or less solid food-masses being voluntarily pushed over the base of the tongue and into the pharynx.

The region of the central nervous system to which the afferent impulses travel is, according to Marckwald,[4] situated in the floor of the fourth ventricle, above the centre of respiration. From this centre of deglutition in the medulla pass out the motor impulses, which, distributed by a variety of nerves, produce the remarkably rapid and orderly sequence of movements that give the bolus its initial push and continue it on its course. By the hypoglossus nerve impulses pass to the tongue, by the third branch of the trigeminus to the mylo-hyoid, by the glosso-pharyngeus and the pharyngeal branch of the vagi to the muscles of the pharynx, and by several vagus branches to the entire length of the œsophagus. We can readily understand into what a chaos all this wonderfully co-ordinated mechanism is thrown by the incidence of bulbar disease.

We shall now turn our attention to the important part played by the vagi in the nervous control of the œsophagus. According to Kahn,[5] the innervation of the thoracic portion of the œsophagus is the same in the cat, dog, and monkey—merely the œsophageal branches of the vagi which enter the wall of the tube just above the hilus of the lungs. Still other branches, however, enter the wall near the diaphragm. To the neck region, in all three animals, the recurrent laryngeus supplies motor fibres—in the dog and cat only to the lower portion, but in the monkey to the whole extent of the cervical œsophagus. Other branches of the vagi, as well as fibres from the cervical

sympathetic, are distributed directly to the upper portion of the tube in the neck region. Stimulation of the sympathetic fibres produces no obvious effect. Stimulation of the vagus nerve on either side causes strong simultaneous contraction of the entire œsophagus. Clearly the vagi are the motor nerves of the gullet. There are several ways, however, in which they cause an orderly peristaltic wave to progress along the tube.

In 1846, Wild reported experiments which showed that if the œsophagus is divided, or merely has a thread tied tightly about it, the peristaltic wave is definitely blocked at the point of interference. From this observation he drew the conclusion that œsophageal peristalsis is due to a series of reflexes starting in the mucous membrane of the œsophagus itself—a series at once stopped by any interruption of the continuity of the tube.[6] This conclusion was accepted without qualification until 1876, when Mosso published experiments which indicated the possibility of central origin of the peristaltic wave. He used the methods of Wild, but placed a small wooden ball in the œsophagus below the point where the tube had been transected. When a wave, started by a swallowing movement, had traversed the upper section, it did not stop at the point of incision, but in due time reappeared below, and carried the ball to the stomach. Continuation of the wave across an open space led Mosso to a conclusion opposite that of Wild—viz., that œsophageal peristalsis is originated step by step in the central nervous system.

The discrepancy between Wild's and Mosso's observations and inferences had no explanation until Meltzer, in 1899, repeated the experiments, and was able by varying the conditions to obtain one result or the other, as he pleased. The key to the situation lay in recognizing the effect of anæsthesia. In very deep anæsthesia water can be introduced into the mouth, and no deglutition will follow. When anæsthesia is slightly less deep, reflex contractions of buccal and pharnygeal muscles occur, but they are not followed by œsophageal peristalsis. With still less deep anæsthesia a peristaltic wave follows a swallow if material is pressed into the gullet from the mouth, but fails if the swallow is empty. It therefore fails also beyond a compressed or incised region. With very light anæsthesia the entire process occurs quite normally, and the wave will pass an interruption in the continuity of the tube. According to Meltzer's results, Wild observed conditions which appear in deep anæsthesia, and discovered

the reflex peristalsis which can originate in the œsophagus itself. Mosso, on the other hand, who studied the conditions in light anæsthesia, discovered the central origin of the procession of œsophageal peristalsis, which normally prevails.[7]

Two mechanisms are therefore present to control the course of a bolus along the gullet. One mechanism requires only a single afferent impulse to start it, the impulse arising usually at the chief or most sensitive spot in the mouth or pharynx. This ingoing impulse spreads in the centre for deglutition, and in proper order evokes the series of nervous discharges which precipitate the rapid sequence of contractions in the mouth and throat, and move the annular constrictions along the œsophagus, which constitute normal deglutition. The continuity of the gullet is not necessary for the progress of this form of peristalsis, but its nervous control is especially sensitive to anæsthetics. Meltzer suggests calling this the higher reflex mechanism, which gives rise to "primary peristalsis." The other mechanism consists of a succession of reflexes, each provided with an afferent path which leads to a motor discharge to the region immediately above. Thus the bolus by its very presence would cause a contraction which would press it downwards to the stomach. This accessory mechanism is dependent on the integrity of the œsophageal tube, and, although requiring the presence of both vagus nerves, is more resistant than the higher mechanism to anæsthetics. It has been called the lower reflex mechanism, and its activity "secondary peristalsis."[8]

The observations of Kronecker and Meltzer on the innervation of deglutition were concerned with influences affecting the process through its central control. When a series of swallowing movements were made, as in drinking a glass of water, they found that the peristaltic wave appeared only after the last swallow. Thus each act of deglutition can not only rouse its own œsophageal contraction, but can at the same time inhibit the appearance of an œsophageal contraction in process of being roused by a previous swallow. On the other hand, if a peristaltic wave has just been started when another swallow is taken, this first wave is not stopped by the second swallow, nor is there a superposition of a second wave on the first. The second motor discharge is only sent out after the contraction following the first discharge has been completed. There is, then, here a clear refractory phase which prevents continuous contraction of the

œsophageal muscles. The inhibitory mechanism Kronecker and Meltzer were able to bring into action by exciting the glosso-pharyngeal nerve; whereupon the strongest stimuli to deglutition were without effect. That the glosso-pharyngeus exercises a tonic inhibitory influence* is indicated by the effect of cutting it: the œsophagus enters a tonic contraction which may persist for more than a day.[9]

Although œsophageal peristalsis resembles in appearance gastric and intestinal peristalsis, nevertheless the waves passing along the gullet, unlike those of the rest of the alimentary canal, have come to be regarded as due exclusively to impulses arriving by way of the vagi. Thus, Meltzer[10] states: "It is now generally assumed that the orderly progress of the peristalsis in the œsophagus is exclusively of central origin." More recently Starling[11] has declared: "The orderly progression of the peristaltic wave along the walls of the tube (œsophagus) is dependent on the integrity of the branches of the vagus nerve, by which the medullary centre is united to the gullet. Division of these nerves destroys the power of swallowing."

The evidence that œsophageal peristalsis is managed through the vagi is found, as we have seen, in the anatomical distribution of the nerves to the tube, and, as just indicated, in the effect of cutting these nerves. Thus secondary peristalsis was entirely abolished, Meltzer observed, as soon as the vagi were severed; and the material introduced was no longer moved downward.[12] This stasis of food in the œsophagus after vagus section was, indeed, recorded by Reid as long ago as 1839.[13] Reid's observations were quoted by Volkmann,[14] and Volkmann's article has been repeatedly referred to by recent writers as authority for the failure of deglutition after severance of the vagi.

In enunciating the doctrine that extrinsic innervation of the œsophagus is the necessary condition for activity, two important considerations seem to have been overlooked—first, the difference between the immediate effects of vagus section and the later possible recovery of a normal state; and, second, the muscular structure of the lower fourth or fifth of the tube, which, as we have noted, is composed in many animals largely or entirely

* The reader will recall that the glosso-pharyngeus has been reported as the afferent nerve for the initiation of swallowing. Possibly the observation of Kitajew (*Jahresb. ü. d. Fortschr. d. Physiol.*, 1908, p. 151), that weak stimulation of this nerve inhibits deglutition, while strong stimulation causes frequent and strong contractions of the œsophagus, gives a clue to the discrepancy.

of smooth fibres, well supplied with a myenteric plexus, and resembling in all essentials the muscular wall of the stomach and intestine. In 1906 I had occasion to observe that there may be for some time after vagus section a total absence or notable inefficiency of gastric peristalsis, with a subsequent remarkable restoration of function. The local mechanisms, at first inert after removal of vagus influence, later prove able to continue gastric peristalsis in an almost normal manner.[15] If it is possible for the stomach thus to recover from a primary paralysis, may not the œsophagus, at least that part of it similar in all essential respects to the stomach structure, be able to recover likewise from a primary paralysis ?

An answer to the question was found by severing in the cat, the lower fourth of whose œsophagus is supplied with smooth muscle, the two vagus nerves*—the right below the origin of the recurrent laryngeal, the left in the neck—and subsequently studying by means of the X rays the movements of the food in the œsophagus. An account of a typical case will present the results.

Two days after section of the right vagus nerve, the left was cut, but just before the second operation meat wrapped about some bismuth subnitrate was seen moving regularly along the œsophagus and into the stomach. The next day finely ground meat was fed ; it was carried normally through the cervical portion of the tube, but promptly stopped at the top of the thorax. As bolus after bolus was swallowed, the thoracic œsophagus became filled with a distending mass. Continuous observation for forty-five minutes revealed no sign of activity in the gullet, and no food entered the stomach.

On the day following—the second day after severance of the left vagus nerve—nothing of the accumulated mass was found in the œsophagus. Now a spoonful of mush mixed with subnitrate of bismuth was given. It was quickly passed to the top of the thorax, and in four minutes it was spread, apparently by rhythmic changes of pressure due to respiration, as a long, slender mass even to the diaphragm. During another four minutes the mass lay without being further affected. Then a second spoonful of the mush was given. When this new material was pressed into the thoracic œsophagus, the lumen was enlarged to almost twice its former diameter. Immediately a constriction of the œsophageal wall occurred at the level of the lower half of the heart. This constriction moved toward the stomach,

* In all operations the animals were, of course, under complete general anæsthesia.

and was followed by others that also moved downward. The first waves failed to drive food through the cardia; the food slipped back through the moving ring. Later waves, however, were more effective, and pushed food into the stomach. The remnant of the mush in the gullet was now extended again in a slender strand. During ten minutes more of continuous observation, no further change was seen. The next morning there was no food in the cage and none in the œsophagus. The waste was in the large intestine.

On the third day the animal took three spoonfuls of the food, which filled the thoracic œsophagus to stretching. Immediately, at the level of the lower half of the heart, a constriction appeared that passed downward, causing as it moved a marked bulging of the tube in front. Some of the food surely escaped backward through the advancing ring. This wave was immediately followed by a second, starting from the heart level, and pushing downward in a manner similar to the first. The second wave forced food into the stomach. The remnant became extended to the diaphragm; but only after four minutes did another ring start at the heart level, and push the lower end of the column into the stomach. Again the remnant was extended to the diaphragm. Except occasional deep stationary constrictions, at the heart level, there was no change for eight minutes. Then a ring formed just above the diaphragm, and pushed food into the stomach; and another ring, immediately above, cut off the lower end of the remaining mass, and likewise forced this bit of food through the cardia. The rest of the œsophageal accumulation was now but a slight strand in the upper thoracic region. For thirty-eight minutes of observation it remained unmoved in that situation.

On the seventh day the thoracic œsophagus was filled, through a rubber tube, with thin starch paste (3 grammes to 100 c.c. water) mixed with bismuth subnitrate. At once after the injection, one constriction after another formed in rapid succession, each cutting off the extremity of the repeatedly extended mass and moving it through the cardia. As judged by gently feeling the larynx, there was no swallowing in this process; the action was a local response to the presence of material in the lower gullet. Thus, by repeated reductions from below, the column of food was gradually carried away until only a slender remnant was left. This was slowly moved below the heart, but there it stayed for half an hour. At the end of that period a small bit of meat, with bismuth subnitrate adherent, was fed. The meat moved smoothly through the cervical region, but stopped at the top of the thorax. Now the slender mass below was gathered together and swept into the stomach. Sixteen minutes were required for the meat to come to the level of

the lower half of the heart. Again nothing interpretable as a constriction was seen in the thoracic œsophagus above the heart. Below the heart, however, the meat, which had been separated into two pieces, was carried by peristalsis into the stomach.

Twenty-three days later the animal was again given starch paste as before, with the same results. While there was still a considerable amount of the paste above the heart level, swallowing movements were caused by tickling the larynx. Most careful scrutiny showed no sign of the passage of a wave over the food in the upper thoracic region.

In the foregoing record of the gradual recovery of function in the lower œsophagus, several points stand out significantly :

1. Immediately after operation, and for twenty-four hours at least thereafter, it is easy to gather evidence of complete paralysis of the œsophagus. In one instance during this first period food was observed stagnating in the gullet for five hours, and in another instance for seven hours, after feeding. But evidently in the cat a distinction must be made between this primary paralysis of the whole œsophagus after bilateral vagotomy, and a secondary recovery of certainly the lower half of the thoracic portion.

2. After a return of peristaltic activity in the lower œsophagus, an important factor for arousing that activity seems to be the stretching of the œsophageal wall. A slender mass spread along the tube may lie for some time unmoved ; the addition of a second mass, which causes a stretching of the wall, results in the instant appearance of circular constrictions and peristaltic movements. And, similarly, after repeated reductions have rendered the strand of food more attenuated, it lies for longer periods unaffected by œsophageal contractions. The reaction of the œsophageal wall to the presence of a stretching mass is a local reaction, occurring without centrally initiated movements of deglutition. In this respect it is similar to movements of the alimentary canal below the cardia. The lower œsophagus seems to become more responsive to the presence of contained material as time elapses, for the material is driven into the stomach with increasing rapidity, and even slender masses are sufficient cause for peristalsis. Apparently the recovery of activity is due to a restoration, in some manner, of the capacity for exhibiting tension when stretched—a capacity ordinarily maintained by vagus influences, but intrinsically developed when

those influences are lost. This, however, is a fundamental matter which we must deal with later.

3. A difficulty in forcing food through the cardia explains to some extent the slower emptying of the gullet during the first days after operation. That the cardia of the cat offers an obstacle to easy passage into the stomach after bilateral vagotomy, is proved by the fact that strong peristaltic waves, so strong as to produce a very marked bulging of the tube in front of them as they advance, have failed to force food into the stomach. Indeed, three days after cutting the second vagus nerve I have seen almost exactly the same repetition of deep constrictions and vigorous peristaltic movements in the lower œsophagus as occur in the small intestine in case of obstruction.[16] The opposition at the cardia was also noted when in these animals attempts were made to pass a tube into the stomach.

4. Throughout these observations a marked contrast was noted between the activity of the lower half of the thoracic œsophagus and the persistent inactivity of the upper half. Absence of peristalsis from the region above the heart was as true a month after the second vagus was severed as it was during the first twenty-four hours. Is there any difference of condition between these two parts of the thoracic œsophagus which might account for their difference of action after vagus section? Leaving one recurrent laryngeal nerve, as we know, still provides innervation for the cervical œsophagus; but cutting off all vagus supply, except one recurrent laryngeal, destroys the extrinsic innervation of the gullet between the base of the neck and the cardia. In this thoracic region the œsophagus is provided with two kinds of muscular fibres. A histological examination of the œsophagus of the animal on which were made the detailed observations reported above showed that the musculature of the upper half of the thoracic region was composed predominantly of striped fibres, whereas the musculature of the lower half, over which peristalsis continued after vagus section, was composed almost wholly of unstriped fibres. Since the difference between the cervical œsophagus, which acted normally, and the upper thoracic œsophagus, which failed to act, was that the former had in all cases a recurrent laryngeal supply, while the latter had no outside nerve connection, the conclusion is justified that that part of the tube which is composed of striped muscles fibres is paralyzed when vagus impulses are removed from

it. The general conclusion, however, that the entire œsophagus is put out of action by severance of the vagi must be modified. That part of the tube which is composed of unstriped muscle is, like other similar parts of the alimentary canal, capable of quite perfect peristaltic activity without the aid of extrinsic nerves.

The validity of these conclusions was confirmed by observations on the rabbit and the monkey (rhesus). In the rabbit no œsophageal peristalsis was seen at any time after severance of the second vagus nerve, although one animal was kept alive and examined from time to time for two weeks after the operation. In the monkey, on the other hand, the results were similar to those in the cat. Three hours after the second vagus was sectioned, mashed banana mixed with subnitrate of bismuth, swallowed by the monkey, was at once carried to the upper thoracic œsophagus, where it rested. More banana forced some of the mass in the gullet to the level of the heart. As soon as it reached beyond this level, the food was promptly separated and carried slowly into the stomach. There was no evidence of obstruction at the cardia. For further assurance the animal was etherized, the right vagus also severed in the neck, the left thoracic wall widely opened, and the œsophagus watched directly, as water was introduced through a tube into the cervical portion. Where the vessels of the left lung crossed the gullet, peristaltic waves appeared, and moved slowly downward until they went out of sight behind the diaphragm. The point where the waves were first seen was marked by making a deep cut, and the animal was then killed. The œsophagus of the rabbit longest observed and the œsophagus of the monkey received careful histological examination. Striped muscle, almost exclusively, was seen throughout the length of the rabbit's œsophagus. The part of the monkey's œsophagus above the cut—the part which was paralyzed—was composed entirely of striped fibres; the part below the cut had only a few scattered striped fibres, the rest was all smooth muscle.

Mosso's observations revealed an œsophageal peristalsis of central origin, distinguished by Meltzer as primary peristalsis. Wild's studies disclosed a reflex œsophageal peristalsis of peripheral origin, the secondary peristalsis of Meltzer. To these two varieties, which require vagus support, must be added a third, which can be seen when a portion of the œsophagus is supplied with smooth muscle. The peristalsis of this portion,

like peristalsis below the cardia, is capable of autonomy. In many cases which I have observed, it has been sufficient without vagus support to clear the œsophagus of any ordinary food which had been carried into the thoracic segment. And, as we have already noted, the rapid contraction of the muscles of the mouth are able to discharge fluid food into this region, where independent peristalsis is possible.

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CHAPTER IV

CONDITIONS AFFECTING THE ACTIVITIES OF THE CARDIA

THE thickened band of circular smooth muscle at the junction of the œsophagus with the stomach—the cardiac sphincter, or cardia—has the function of preventing the passage of material from the stomach back into the œsophagus. Normally we are quite unconscious of the nauseating odour and the highly disagreeable taste of the gastric contents, and for this pleasant security the closed cardia is largely responsible. As aids in establishing the barrier between the stomach and the gullet, the sharp angle between the two structures, acting like a valve, and the close grasp of muscle layers in the diaphragm, have been mentioned.[1] Evidence will indicate, however, that these accessory agencies must be regarded as relatively insignificant compared with the tonus of the sphincter.

That the cardia is normally closed has been observed in various ways;—by introducing a finger into the œsophagus from the opened stomach, by direct inspection from below, and by inspection from above through an œsophagoscope. The closed condition can also be inferred from the stoppage of swallowed liquids in the lower gullet until a peristaltic wave arrives and presses them through. Although the contracted state of the sphincter seems continuous, it is capable of exhibiting an alternating increase and decrease—a phenomenon known to Magendie early in the last century.[2] Two activities of the cardiac sphincter, therefore, are to be distinguished—a persistent contracted state or tonus, and at times, superposed on this, rhythmic alternation of contraction and relaxation. In these two manifestations the smooth muscle of the cardia is like the smooth muscle of other parts of the alimentary canal, to be considered later.

The tonic contraction is itself variable in intensity, and can be increased or decreased by a number of conditions. Usually, in a

state of rest, the tonus is not high. The common ease of passage through the sphincter has been observed by several investigators. Mosso noted that a small wooden ball, attached to a thread, could be withdrawn from the stomach without meeting any considerable resistance.[3] On the œsophageal side, v. Mikulicz observed in man that such slight pressure as 2 to 7 centimetres of water was sufficient to drive air or water into the stomach. As a rule the necessary pressure was less than that of a column of fluid which would fill the thoracic œsophagus.[4]

As already stated, a sound can be heard by listening over the region of the cardia, six or seven seconds after liquids have been swallowed. This sound is due to the swallowed material, liquid and air, being pressed through the tonically contracted sphincter. Sometimes this sound is heard immediately after swallowing—a result which Meltzer has attributed to a weakly contracted cardia, because, among other reasons, he observed it in consumptives who easily regurgitated gastric contents while coughing.[5]

Even the slight contraction that normally prevails in the resting cardia can be reduced by nervous influences. During repeated deglutition, for example, the sphincter becomes more and more relaxed as the number of swallows increases, and may be so completely relaxed that no sounds are heard as the fluid passes through into the stomach.[6] In the rabbit with opened abdomen the cardia can be seen to enlarge slightly with each swallowing movement: and if the stomach is filled with air, an act of deglutition is accompanied by the release of air into the œsophagus through the patulous sphincter. As the peristaltic wave descends, it pushes the air downward, and only when the escaped volume is restored to the stomach does the cardia close. This relaxation of the terminal sphincter as a peristaltic wave approaches admirably illustrates the general law that opposed muscles normally act, not in opposition, but in harmony—a law that Meltzer emphasized in this connection.[7]

Following the relaxation of the cardia and the passage of the swallowed bolus, there is a prompt contraction. This contraction, as Kronecker and Meltzer observed, is much more intense and lasts longer, the longer the series of swallowing movements that have preceded.

The nervous path by which the cardia is affected in the process of swallowing is by way of the vagi. Impulses along these nerves

cause, not only the relaxation of the sphincter, but also the subsequent increase of tone. The two effects can be separated by varying the rate and intensity of stimulation.[8] During vagus stimulation in the neck region Langley observed relaxation, and when stimulation ceased, strong contraction of the sphincter. By giving small doses of atropine, he was able to eliminate the motor fibres and produce pure inhibitory effects.[9] Langley[10] has also reported that the cardiac sphincter is relaxed when adrenalin is given; and as the effect of adrenalin is an indicator of the presence and function of sympathetic nerve fibres, the conclusion is justified that the cardia has a sympathetic supply which causes relaxation.

I have already stated that severance of both vagus nerves causes in the cat a temporary increase of tone in the cardiac sphincter (see p. 29). This observation is in accord with the observations of Bernard,[11] Schiff,[12] and Kronecker and Meltzer,[13] that cutting both vagi in the neck is soon followed by strong contraction of the lowest part of the œsophagus. But they are not in accord with the observations of Krehl,[14] that after vagus section the cardia is patulous; nor are they in accord with Katschkowsky's[15] assumption to the same effect. It may be that this conflict of evidence can be explained by the temporal factor. Thus Sinnhuber[16] concludes, from a critical review of the literature and from his own experiments, that, though cutting the vagi may cause the cardia to enter a cramp-like contraction, this is only a temporary state. Starck[17] also does not believe that vagus section produces any lasting hindrance to the passage of food through the cardia. In my experience, the increased tonus of the cat's cardia after bilateral vagotomy usually does not persist as a considerable obstacle, and the forcing of food into the stomach by œsophageal peristalsis becomes in time not difficult. But there have been a few instances in which there was continued trouble in passing a tube into the stomach; the œsophagus in these cases suffered a marked dilatation, and became filled with food which was not removed.

Other conditions affecting the tonic contraction of the cardia have been reported by v. Mikulicz.[18] For example, in his observations on a patient he noted that, when the region of the cardia had been irritated mechanically or chemically, the pressure required to force fluid into the stomach was increased. It was higher for cold drinks and for carbonated water than for warm

water.* These differences in resistance to the passage of different fluids through the cardia were seen also in the dog, but they disappeared when the vagi were cut.

From the stomach side the passage of air into the œsophagus occurs by eructation, according to Kelling,[19] whenever intragastric pressure rises to about 25 centimetres of water. A still easier regurgitation is indicated by the observation of Kronecker that when, after repeated "empty" swallowings, the dog's stomach has been filled with air, the least motion suffices to cause the air to pass back into the œsophagus.[20] Deep anæsthesia, in Kelling's experience, abolishes this ready relaxation of the sphincter, and then the stomach may be inflated to bursting before the air will escape.

Most of the evidence thus far presented indicates a relatively low degree of tonic contraction of the cardiac ring. This condition is not one that assures the retention of gastric contents in the stomach during digestion, which is the normal function of the sphincter. As we shall see, however, a special local and automatic arrangement exists by which the cardia is more firmly closed while gastric digestion is in progress. Before regarding this mechanism for locking the food in the stomach, we must consider the second activity of the cardia previously mentioned—its rhythmic contractions.

The rhythmic oscillations in the contraction of the cardia, as already stated, were known to Magendie nearly a century ago. These variations of contraction, according to Schiff, are not actually localized at the cardia, but result from a ring of constriction moving up and down the lower œsophagus and periodically involving the cardia.[21] Schiff's observations were made on dogs and cats. In 1860, Basslinger described rhythmic pulsations of the cardia in the excised stomach of the rabbit,[22] a phenomenon sometimes designated as "Basslinger's pulse." The cardia of the normal rabbit Kronecker and Meltzer[23] found usually quiet, but in a freshly bled rabbit they saw the spontaneous movements described by Basslinger.

If Schiff's conception of peristalsis and antiperistalsis in the

* In this connection the observation by Kronecker and Meltzer (*Arch. f. Physiol.*, 1883, Suppl., p. 355) may be cited, that carbonated water produces strong persistent spasm of the œsophagus, which cannot be inhibited by subsequent deglutition. This peculiar effect they did not investigate further. A distressing cramp is at times experienced in the region of the cardia, which is at once relieved when accumulated gases are released from the stomach. The observations may be significant in relation to cardiospasm.

lower œsophagus is correct, any regurgitation of gastric contents could take place only slowly and to a slight extent; but if, as Magendie stated, a true diminution of the contracted state occurs, leaving an easily forced passage, gastric contents might be forced backward suddenly and throughout the gullet. The difference between the views of Magendie and Schiff, and the possibility that, after all, their and Basslinger's observations might have resulted, as Kronecker and Meltzer's study suggests, from abnormal conditions, made it desirable to investigate the action of the cardia under more natural conditions.

In 1902, during an attempt to see the movement of particles of food in the stomach when the gastric contents were fluid, I noted repeated regurgitation from the stomach into the œsophagus.[24] The fluid consisted of 100 c.c. of thin starch paste mixed with 5 grammes of subnitrate of bismuth. It was given by stomach-tube. The animal lay comfortably on a holder, unanæsthetized, and was examined by means of the X rays. The regurgitation was unattended by any signs of nausea or retching, and when the animal was lifted from the holder she acted quite as a cat normally acts. The periodically lessened contraction of the cardia would therefore appear to be a natural phenomenon. Since the fluid, on emerging from the stomach, at once passed quickly up the œsophagus to the level of the heart, or even to the base of the neck, it is clear that Magendie's conception was correct, and that Schiff's idea of an oscillating peristalsis and antiperistalsis in the lower œsophagus must be discarded. In fact, no one who has studied the œsophagus directly has ever seen antiperistaltic waves in it.

Each regurgitation, as I watched them, was followed at once by a peristaltic wave which pushed the escaped material back again into the stomach. Soon after it was thus restored, the cardia again relaxed and it again rushed out, only to be restored to the stomach by another peristaltic wave. Thus the process continued. The peristaltic wave was seldom started by voluntary deglutition, but was of the secondary order, stimulated by the presence of the material in the œsophagus.

Regurgitation and restoration of the fluid may thus recur fairly periodically for twenty or thirty minutes. The periods are shorter at first than later. In the following figures are shown the time taken by these periodic movements when a large cat was given 180 c.c. of fluid boiled starch at 3.20 p.m. The figures

under "Out" indicate the moment when the fluid emerged into the œsophagus; those under "In," when the last of the fluid disappeared into the stomach.

Out.	In.	Out.	In.
3·21— 6	3·21—12	3·22—19	3·22—28
17	24	44	51
32	38	23— 2	23— 8
48	54	21	29
22— 2	22— 8	43	49

The regurgitation continued thus, but became gradually less frequent. Twenty minutes after the first observation, appearance and disappearance were as follows:

Out.	In.
3·41—14	3·41—27
42—26	42—42
43—45	43—59
45— 8	45—16

During the eighteen minutes of observation that followed, the food emerged only three times.

In this instance there was a fairly rhythmic appearance of food in the œsophagus, beginning at the rate of four times a minute, gradually falling to three and two times a minute, and ceasing almost entirely soon after a rate of about once per minute was reached.

Two questions are suggested by these observations: Under what circumstances do the regurgitations occur? and, Why, once begun, do they cease?

In answer to the first question, the fluidity of the gastric contents must be regarded as a prime factor in the regurgitations. When the food escapes into the œsophagus, it escapes quickly in a thin stream. If the stomach is full of more or less gross fragments of food, it is quite conceivable that a slight weakening of the contraction of the cardia would not permit such semi-solid material to pass. A second factor in the regurgitation is intragastric pressure. Into the stomach of the cat that furnished the records given above was introduced on one occasion 60 c.c. of the fluid starch, with no regurgitation during the next five minutes; 60 c.c. more was introduced, with no regurgitation during the five minutes that followed; then 60 c.c. more was introduced, making in all 180 c.c., and regurgitations at once began and continued. In order to demonstrate the rhythmic relaxations of the cardia, therefore, the gastric contents must be fluid, and must

be under sufficient pressure to pass through the cardia when its contraction weakens.

At first it seemed that fluidity and pressure were the only factors concerned. The cessation of the regurgitations might then be explained by a slow accommodation of the stomach to the volume of its contents, or by the escape of material into the duodenum until the intragastric pressure was insufficient to press the fluid through the only slightly relaxed cardia. These explanations, however, are not adequate. Kelling has shown that, within limits, intragastric tension is readily adjusted to varying amounts of food, and that for this adjustment only a few moments are required;[25] the normally rapid adjustment of intragastric tension, therefore, would not explain the cessation of the regurgitations after their continuance for twenty or thirty minutes. And observations on the intestinal contents of animals in which the regurgitations have ceased have shown only a small amount of the fluid starch in the intestine. A diminution of intragastric pressure does not, therefore, account for the disappearance of the regurgitations.

Since the repeated escape of fluid food into the œsophagus is dependent on a periodic lessening of the contraction of the cardia and on an intragastric pressure sufficient to force the gastric contents through the weakened barrier, and since intragastric pressure probably does not materially diminish at the time when the regurgitations cease, the explanation of the cessation must lie in a change at the cardia. Either the rhythmic relaxations might be stopped, or the tonus of the sphincter might be increased. With an increased tonus the cardia might, of course, still undergo rhythmic contractions and relaxations, but on a level so much higher than before that the intragastric pressure would now be unable to overtop it. Thus the cardia would perform its normal function of preventing the passage of food backward into the œsophagus during the process of gastric digestion.

What new conditions developed in the stomach during digestion might affect the cardia? The conditions might be of two orders, mechanical or chemical: the actual stretching of the stomach might cause closure of the cardia, as Magendie suggested; or the new secretion poured out by the stomach during digestion might, with its acid reaction, have that effect. As we have learned, the rhythmic relaxations of the cardia are

made manifest only as the content of the stomach is increased. And, furthermore, the gastric wall does not become more stretched by any material increase of the contents, as the food lies in the stomach during twenty or thirty minutes. The stopping of the regurgitations is therefore not explained by increase of intragastric pressure. Is the chemical agency, acid in contact with the gastric mucosa, capable of changing the contraction of the sphincter?

Evidence will be presented later showing that, if acid is continuously injected into the duodenum close beyond the pylorus, that sphincter can be kept closed for an unlimited period. Indeed, this response of the pylorus to the acid illustrates a general law of the alimentary tract, that a stimulus causes a contraction above the stimulated point. And just as acid beyond the pylorus keeps the pylorus closed, so likewise acid in the stomach (beyond the cardia) may keep the cardia closed. Thus an essential condition for digestion in the stomach, the presence of acid, would itself automatically hold a barrier against a return of the contents into the œsophagus.

That a marked acidity of the gastric contents does promptly check regurgitation through the cardia is proved by such observations as the following:

A cat with an empty stomach was given by stomach-tube 200 c.c. fluid starch with 10 grammes bismuth subnitrate at 2.55 p.m. The regurgitations occurred as follows:

Out.	In.	Out	In.
2·56— 1	2·56—11	2·58—38	2·58—49
16	28	58	59—10
32	42	59—30	40
46	57		(cat excited)
57— 8	57—18	3·00—35	3·01— 2
		(cat excited)	
29	39	01—15	25
48	60	44	54
58—12	58—22	02— 2	02—12

At this time no food had passed through the pylorus. The contents of the stomach were now as much as possible removed (about 180 c.c.). The reaction was very faintly acid. Fresh fluid starch was added to make 200 c.c., and then 4 c.c. of 25 per cent. hydrochloric acid was mixed with the fluid, making approximately a 0·5 per cent. acidity, which is normal for carnivora. The fluid was then reintroduced into the same animal at 3.12 p.m., with the following results:

Out.	In.
3·13—45	3·13—53
14—17	14—39

The fluid passed from the stomach into the œsophagus these two times in a very thin stream. Thereafter there was no regurgitation whatever during ten minutes of observation. The cardia was now holding tightly enough to retain gastric contents amounting to 220 c.c., although previous to the acidification it did not withstand the pressure of 200 c.c.

This observation has been repeated on normal animals and on an animal whose splanchnic nerves had previously been severed, with the same results.

The effect of acid in the stomach on the tonus of the cardia can be demonstrated also in the anæsthetized operated animal.

A cat was etherized and also given subcutaneously 1 c.c. of 1 per cent. morphine sulphate in order to maintain uniform anæsthesia. When the animal was thoroughly anæsthetized, the spinal cord was pithed below the brachial region, the stomach exposed, and a tube tied into the cardiac end by means of a ligature encircling the organ. Another tube was introduced through the cervical œsophagus as far as the upper thorax, and tied in place. Each tube was connected by rubber tubing with a long upright thistle tube. Warm physiological salt solution was now introduced until the level in each tube was 9 centimetres above the cardia. At once the fluid in the œsophageal tube began to disappear and reappear at fairly regular intervals, precisely as in the X-ray observations on regurgitation.

After the rhythmic regurgitation had proceeded for several minutes the salt solution was removed. It was replaced by a similar solution containing 0·5 per cent. hydrochloric acid, poured into the thistle tube connected with the stomach. The acidulated salt solution was added until it rose 19 centimetres above the cardia. For several minutes it stood at that point, with no relaxation of the sphincter. The stomach was now compressed, and the fluid rose 33 centimetres above the cardia before the sphincter relaxed. The fluid that then passed into the œsophagus was immediately pushed back into the stomach by peristalsis and held there. Pressure again applied to the stomach forced the column of salt solution to 42 centimetres above the cardia before relaxation again occurred. No rhythmic regurgitation was observed.

Now the acidulated salt solution was removed from the stomach and replaced by 1 per cent. sodium bicarbonate, poured into the stomach-tube until 9 centimetres above the cardia. Almost immediately regurgitations began, and continued rhythmically during ten minutes of observation.

The closure of the cardia by intragastric acidity can be registered graphically by connecting the œsophageal tube, described in the foregoing experiment, with a recording tambour. The regurgitations into the œsophagus cause the writing lever of the tambour to rise, and as the regurgitated fluid is carried back into the stomach the lever falls. Fig. 1 presents a record of such regurgitations. The glass tube tied into the cardiac end of the stomach was short, and connecting it with a thistle tube was a piece of rubber tubing. Through the rubber tubing a hollow needle was introduced into the gastric cavity. Thus the stomach was not disturbed in the subsequent experimental manipulation. During the period indicated by the broad black line at A, sufficient hydrochloric acid (2 c.c.) was introduced

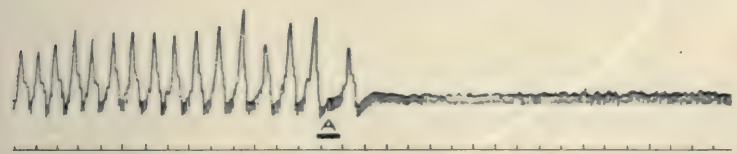

FIG. 1.—RECORD SHOWING CESSATION OF RHYTHMIC REGURGITATIONS OF FLUID FROM THE STOMACH INTO THE ŒSOPHAGUS ON ACIDULATION OF GASTRIC CONTENTS.

The upstroke of the larger oscillations represents the outflow, and the downstroke the return of the fluid to the stomach by œsophageal peristalsis. The small oscillations are due to respiration. The time is marked in half-minute intervals.

through the needle into the stomach to render the salt solution acid to 0·5 per cent. After one more regurgitation the cardia closed.

The question now arises as to whether the effect of the acid on the cardia is a local effect, or mediated through the vagus or splanchnic nerves. That regurgitations continue after splanchnic section, and may be caused to stop by rendering the gastric contents acid, has already been noted. The task of eliminating the vagus nerves is more difficult, because, as we have learned, only the lowest few centimetres of the œsophagus remain capable of peristalsis after vagotomy, and this portion did not give clear records of a restoration of regurgitated fluid into the stomach. The effect of the acid can be tested, however, by observing the intragastric pressure required to open the cardia before and after the acidulation of the fluid.

A cat with the vagus nerves severed several days previously was prepared for observation in the manner above described.

Warm salt solution was poured into the thistle tube connected with the stomach until the pressure was 14 centimetres, rising to 19 centimetres during inspiration. Only then did the cardia relax. A second determination resulted in the same figures.

The salt solution, which proved to be neutral, was now removed and replaced by the same solution containing 0·5 per cent. hydrochloric acid. The acid fluid was poured into the tube tied into the stomach until the pressure was 17 centimetres (rising to 22 centimetres during inspiration) before the cardia relaxed. The fluid was now removed and immediately again poured into the stomach ; this time the pressure rose to 19 centimetres (24 and 25 centimetres during inspiration) before the cardia opened. Another immediate repetition gave 21 centimetres rising to 26 and 27 centimetres, as threshold pressures. In a fourth trial the pressure was raised to 53 centimetres, and the sphincter gave way only when still more fluid was poured into the tube.

In this experiment, as well as in those in which regurgitations were observed and registered, a more or less prolonged latent period intervened between the application of the acid and its full effect in closing the cardia. But the fact that the liminal pressure gradually rose in this instance, and finally became almost four times as great with acid gastric contents as it was with neutral gastric contents, proves that the effect of the acid is not produced through extrinsic nerves, but by the local reflex in the wall of the gut. This result has been confirmed by similar observations made immediately after pithing the lumbar and thoracic cord and severing the vagus nerves.

Does not the prolonged period of regurgitation observed when fluid starch was given (frequently twenty or thirty minutes after its introduction) indicate that the acid mechanism of the cardia is rather defective ? In considering this question, we should remember that boiled starch has very little effect in exciting the flow of gastric juice,[26] and that the cardia therefore probably exhibits relaxations for a much longer period when fluid starch is given than when foods more favourable to gastric secretion are fed.

The fluid character of the boiled starch is also unfavourable to the early closure of the cardia, for the acid secreted is not kept in contact with the wall of the stomach, but is diffused into the fluid ; and each movement of the fluid to and fro between stomach and œsophagus serves to mix the secreted acid with

the total contents. For this reason it was impossible to get consistent results in attempting to determine the acidity of the gastric contents under these circumstances. When the food is less fluid, the acid reaction of the contents of the cardiac end of the stomach is found solely on the surface, near the mucosa, for a considerable period after digestion has commenced. Under these circumstances the conditions for closure of the cardia are most favourable.

A return of material from the stomach to the œsophagus in dogs has been reported by Kast.[27] Lycopodium spores introduced through a gastric fistula into the stomach often appeared after half an hour at an œsophageal fistula in the neck. This reversed movement of material in the œsophagus was not attended by any retching or vomiting. To test whether this return from the stomach might be true of human beings, eleven patients were given, after supper, lycopodium spores carefully enclosed in a gelatine capsule. As a further precaution, the capsule was enveloped in a wafer, and was then quickly swallowed with the aid of water. In six of the eleven cases spores were found in the mouth washings next morning, and in none of these were any spores found in mouth washings taken one or two hours after the capsule was swallowed. It is altogether probable that in the positive cases the cardia must have relaxed to permit the exit of material into the œsophagus. Thereafter the fluids bearing the very fine seeds may have been slowly spread toward the mouth by alterations of pressure due to respiration and the heart-beat, much as swallowed material is spread through the paralyzed gullet. Indeed, with a weakened cardia, the descending diaphragm, by pressing on the stomach while lessening intrathoracic pressure, could pump fluid from the stomach towards the mouth. Kast suggests that the disagreeable taste and the coating of the tongue in gastric disturbance may result from the adhesion to its rough surface of partly digested bits of food, leucocytes and epithelial cells that have come back from the stomach. This suggestion gains interest in connection with our discussion of the acid closure of the cardia, for the coated tongue appears especially in cases of abnormal fermentation of gastric contents which results from deficient hydrochloric acid. This is precisely the condition for a relaxed cardia.

Although the evidence points to the acid control of the cardia

through a local reflex, we must not forget that the cardia is nevertheless under the influence of extrinsic nerves, and that in abnormal states these nerves may cause the sphincter to relax, and permit regurgitation of food that is acid. The common regurgitation of gases may be due to their effect in keeping the acid contents away from the stomach wall in the region of the cardia. Then, as the cardia relaxes and permits the regurgitation of gas, acid fluid may also escape before the sphincter again closes. All these conditions, however, cannot be regarded as normal. Normally, after we have swallowed our food and the automatic processes of the stomach have begun to work their changes in it, one of the automatisms—the acid closure of the cardia—has the function of preventing a backward escape of the gastric contents into the mouth. If in the performance of this important function a slip occurs, and the contents start to escape, the secondary peristalsis of the gullet is able, as we have seen, to bring to the cardia important aid.

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CHAPTER V

THE MOVEMENTS OF THE STOMACH

The function of the stomach as reservoir, ready to receive within a short period a generous provision of food, and arranged to deliver this food to the intestine during a much longer period, in proper amount and at proper intervals, has already been mentioned. This reservoir, however, is itself a place of active digestion. In it the ptyalin of saliva can continue to act for an hour or more, if the amount of food taken is large. And the peptic digestion peculiar to the stomach is an important preliminary to the completion of proteolysis by the action of trypsin and erepsin in the intestine. Even *in vitro* the course of tryptic digestion is more rapid and more intense if it has been preceded by peptic digestion ;[1] while erepsin, incapable by itself of attacking most natural proteins, must await the changes wrought by the other enzymes before it can become effective. The sequence of action of these ferments in an order which gives greatest efficiency is only one of many instances of remarkable interrelations in the digestive canal.[2] Besides being a receptacle for ingested food, therefore, the stomach is also the seat of important preparatory stages of digestion. In promoting these digestive changes, the other mechanical activities of the stomach play their part, by churning together food and secretions. And when this process has proceeded to a proper stage, they propel the altered food onward for further digestion, as rapidly as the duodenum is ready to receive it. The functions of acting as reservoir, and of mixing and propelling the food, are performed by different parts of the organ.

The anatomy of the stomach with reference to its varying form has been carefully discussed by Cunningham.[3] Since he has considered the relation between the structure of the organ and its physiological alterations of shape, we can safely follow

in the main his description. Two portions are to be distinguished—a cardiac and a pyloric portion. The demarcation between the two appears on the lesser curvature as a notch or angular depression—the " incisura angularis."

The fundus is separated from the rest of the cardiac portion by an imaginary line passing around the stomach from the cardiac orifice to the opposite point on the greater curvature. In man it is defined as the part lying above a horizontal plane passed through the cardia. That part of the cardiac portion lying between the fundus and the incisura angularis (called by His the " body " of the stomach[4]) has, when full, a tapering shape. This shape is, as we shall later learn, of considerable significance for the origin of gastric peristalsis.

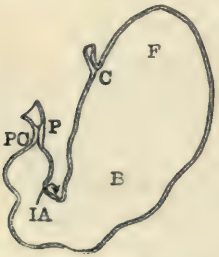

FIG. 2. — SCHEMATIC OUTLINE OF THE STOMACH.

At C is the cardia; F, fundus; IA, incisura angularis; B, body; PC, pyloric canal; P, pylorus.

The pyloric portion, to the right of the incisura angularis, is divisible into the pyloric vestibule and the pyloric canal. The canal, which in man is about 3 centimetres long, is a region more or less tubular in form, but always so contracted as to be clearly marked off from the vestibule. The vestibule lies between the incisura angularis and the pyloric canal, and in the resting stomach is usually pouched into the greater curvature. The term " antrum pylori," meaningless because of its varied uses, we shall discard.

The wall of the stomach consists of three coats, but our interest centres on the activities of the muscular coat. The muscles are arranged in an outer longitudinal layer, a middle circular layer, and a set of inner oblique fibres. The longitudinal fibres continue those of the œsophagus, and, radiating over the cardiac end, become more marked along the greater and lesser curvatures than on the ventral and dorsal surfaces. Over the pyloric portion they lie in a thick uniform layer terminating almost wholly at the pylorus. The circular fibres, arranged in rings at right angles to the curved axis of the stomach, form a complete investment. Toward the pyloric end they become gradually more numerous, and around the pyloric canal they form a very well defined stratum, increasing in thickness towards the duodenum, and at the duodeno-pyloric junction forming

the strong pyloric sphincter. The sphincter is clearly separated from the circular coat of the duodenum by a distinct septum of connective tissue—an interruption of continuity with physiological significance. At the incisura angularis is another special thickening of the circular fibres, called by early writers the "transverse band." The oblique fibres start from the left of the cardia, and pass as two strong bands along the anterior part of the dorsal and ventral surfaces, giving off fine fasciculi to the circular layer; towards the pyloric portion they gradually disappear. It is probable that these bands have an interesting function only recently suspected.

In 1898, Dr. F. H. Williams and I made observations on the changes of form of the normal human stomach during digestion.[5] We found that while early in gastric digestion, when the subject was standing, the greater curvature might reach several centimetres below the umbilicus (the pylorus being then considerably above this level), in the later stages, as the stomach shortens, the pylorus becomes the lowest point. The changes suggested that the contraction of the longitudinal and oblique fibres between the two fixed points, cardia and pylorus, resulted in a tendency for the lumen to take a more nearly straight course between the two orifices.[6] X-ray observations by Morton and Hertz[7] on seventeen healthy young men show that in the vertical position the greater curvature lies from 1 to 12 centimetres below the umbilicus. Nothing is stated regarding the amount of gastric contents in these cases, an important consideration, as we have seen. After an extensive X-ray study of the shape and position of the stomach, Holzknect[8] has declared that the "normal" human stomach is one in which the pylorus is the lowest point. The same view was expressed by Pfahler, who, after X-ray examination of thirty-one healthy persons, declared that the essential point of the normal stomach is that "the pylorus be on a level with the lower pole."[9] Although both Holzknect and Pfahler admit that the normal stomach is relatively rare, they support their opinion by the argument that the stomach is a reservoir, that a reservoir should always be placed higher than its outlet, and that therefore the "normal" stomach is always set above the pyloric outlet as its lowest point.

The view expressed by Holzknect and Pfahler is in agreement with an unfortunate conception of the emptying of the stomach which has in the past prevailed among some surgeons, who have

assumed that the stomach is emptied by gravity drainage. We need not do more than note in passing that in the obviously normal stomach of the dog or cat the pylorus is nearly the highest point when the animal is in the standing position, and that the so-called "normal" human stomach could remain satisfactory for gravity drainage only so long as a person holds the upright position or lies on his right side. A shift to the left side upsets the nice hydraulic arrangement, for it places the pylorus at the highest point of the stomach, and then how can the contents pass out?

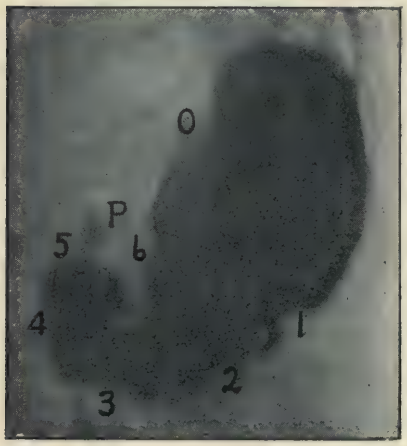

FIG. 3.—OUTLINES OF AN ALMOST INSTANTANEOUS RADIOGRAPH OF THE STOMACH (CAT) DURING DIGESTION.

O = cardia; P = pylorus. At 1, 2, 3, 4, and 5, are indentations due to a series of constriction rings (peristaltic waves) passing towards the pylorus.

The essential fallacy in the idea of gravity drainage from the stomach results from a failure to regard the pressure relations in the abdominal cavity. The weight of the alimentary canal, as such, is approximately that of water. The food swallowed or undergoing gastric digestion has approximately the weight of water. The pressure in any part of the inactive alimentary canal, as Weisker proved,[10] is due to the weight of the overlying abdominal organs. If the canal is inactive, therefore, the food is as if surrounded by water. Water resting in water is, of course, in exact equilibrium. And even when the body is in the upright position, and a large artificial opening connects the stomach and the intestine, water will not run out: "because of the hydrostatic relations in the abdomen, gravity can have no effect."[11] "Drainage" in the common usage of that term is therefore impossible. That the food may move onward through the alimentary canal, muscular contraction is necessary to create a difference of pressure.

The muscular activity of the stomach is exhibited differently at the two ends. Near the middle of the body of the stomach (at 1 to 6, Fig. 3) peristaltic waves take their origin, and course

towards the pylorus. The region above 1 to 6 usually exerts merely a tonic grasp on its contents, and does not display peristalsis. By a study of the pressure at various parts of the stomach in man, Moritz[12] and v. Pfungen[13] inferred that the cardiac end of the stomach must be quiet, and that the motor functions were performed mainly by the pyloric end. The same conclusion was earlier expressed by Leven.[14] Not until the X rays were used, however, was the evidence of the way in

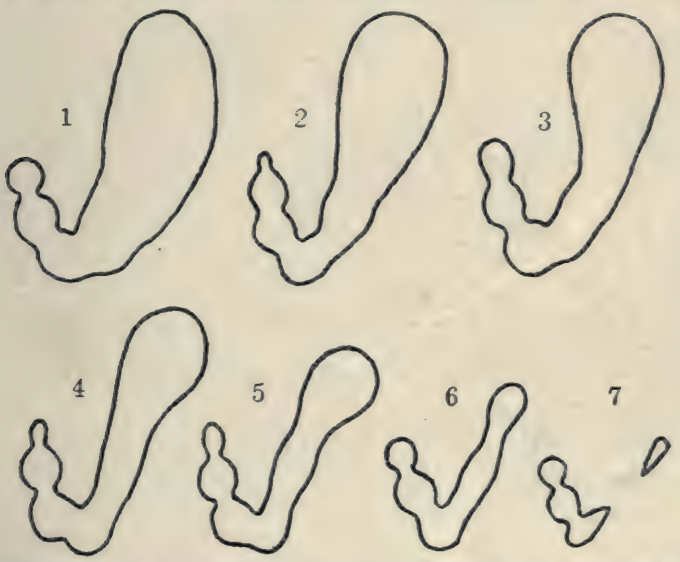

FIG. 4.—TRACINGS OF THE SHADOW CAST BY THE STOMACH (CAT), SHOWING CHANGES IN THE SHAPE OF THE ORGAN AT INTERVALS OF AN HOUR DURING THE DIGESTION OF A MEAL.

which the two regions of the stomach perform their separable functions clear and decisive.

The significance of these two physiologically distinct regions is indicated by outlines of the shadow of the stomach made at regular intervals during digestion (see Fig. 4).* Comparison of these tracings shows that as digestion proceeds the change of form in the pyloric portion is relatively slight. The first region to decrease in size is that part of the body of the stomach over which the waves are passing. As food is discharged into the intestine, the circular muscle of this middle region of the stomach

* For a more complete series, see Cannon, *Am. J. Physiol.*, 1898, i., pp. 370-372.

contracts tonically until (Fig. 4, 2 and 3) a tube is formed, with the full cardiac pouch at the upper end, and the active pyloric portion at the other. Along the tube shallow peristaltic waves still continue. Now the radiating fibres at the cardiac end begin to squeeze the contents into the tubular portion. This process, accompanied by a slight shortening of the tube, continues until the shadow cast by the contents is almost obliterated (Fig. 4, 6 and 7). The waves of constriction moving along the tubular portion press the food onward as fast as they receive it from the contracting cardiac pouch, and when the pouch is at last emptied they sweep the contents of the tube into the vestibule. There the operation is continued by deeper constrictions, till finally nothing but a slight trace of food in the cardiac end is to be seen.

On the basis of this description of the changes in the cat's stomach, Cunningham has examined post mortem the form of the organ in man, and has found not infrequently a similar tubular part extending from the middle of the body to the pylorus, and distinctly separable from the saccular cardiac end. X-ray observations in man reveal the same conditions. In accordance with these facts, Cunningham has suggested the term " cardiac sac " and " gastric tube " to designate these two portions of the stomach.

Concerning the action of the cardiac pouch or sac, little more need be stated. Since it lies close beneath the diaphragm, it is exposed to repeated gentle pressure with each respiration. Since the upper border of the sac is moved more than the lower border, the contents must be slightly kneaded by the alternate contraction of the diaphragm and the muscles of the abdominal wall.[15]

The function of the stomach as a reservoir serving out its contents a little at a time, so that the intestinal digestive processes are not overwhelmed by the sudden arrival of a great mass of material, is at first performed by the entire organ, but later is chiefly performed by the cardiac sac. The advantage thus secured to the intestines can be claimed also for the stomach itself. For, as the foregoing description indicates, and as experiments to be described later will prove, the stomach mixes its secretion with the food in the busy vestibule over which, throughout the period of gastric digestion, constriction waves are continuously running; and the cardiac sac, an active reservoir, presses out its contents little by little as the churning mechanism in the pyloric end is ready to receive them.

Concerning gastric peristalsis two views have long been held. According to the older view, which still has its supporters,[16] the stomach is completely divided at the transverse band by each recurrent wave, and the vestibule then contracts simultaneously in all parts in a systolic manner. According to the newer view, developed by recent research, the waves sweep from their origin to the pylorus, and do not partition the stomach into two chambers. Since the conception of the course of gastric peristalsis affects in an important way the conception of its functions, we may profitably consider the evidence presented in support of the two views.

Beaumont, in his famous experiments on Alexis St. Martin, observed how a thermometer tube introduced through the fistula was affected by the motions of the stomach, and drew the following conclusions: "The circular or transverse muscles contract progressively from left to right. When the impulse arrives at the *transverse band*, this is excited to more forcible contraction, and, closing upon the alimentary matter and fluids contained in the pyloric end, prevents their regurgitation. The muscles of the pyloric end, now contracting upon the contents contained there, separate and expel some portion of the chyme."[17] In close accord with this description of the movements of the human stomach is the account given by Hofmeister and Schutz of the activities of the excised stomach of the dog.[18] The stomach, which was placed in a moist chamber kept at body temperature, remained active for from sixty to ninety minutes. A typical movement of the organ consisted of two phases. In the first phase a constriction of the circular fibres started a few centimetres from the cardia, and passed towards the pylorus. As the constriction proceeded, it increased in strength until a maximum was reached about 2 centimetres in front of the vestibule. This annular contraction, called by Hofmeister and Schutz the "preantral constriction," closed the first phase. Immediately thereafter the strong transverse band contracted and shut off the vestibule from the remainder of the stomach. Immediately a general contraction of the muscles of the pyloric end followed. Relaxation began at the transverse band, and progressed slowly towards the pylorus. Moritz,[19] who studied gastric movements by introducing recording balloons into the dog and man, and Ducceschi,[20] who used the same method in the dog, found marked alterations of the pressure in the pyloric

end, which were not transmitted to the cardiac end. They inferred, therefore, that the pyloric end, separated from the remainder of the stomach, had its own distinct systole and diastole. By introducing the gastroscope through fistulas in dogs and men, Kelling noted so great a narrowing in the region of the transverse band that large pieces of food (lumps of bread) were lying before it.[21] Inference as to the functioning of the transverse band was drawn by Schemiakine, who, while watching through a fistula at the pylorus, noted that the food was not continuously present there, but came in separate allotments.[22] Kaufmann's experimental evidence that vagus stimulation produced complete contraction of the band may be added.[23] And more recently Auer has reported that in the rabbit, when extrinsic nerves have been severed, gastric peristalsis is emphasized at the transverse band by a deep constriction, which divides the stomach, and that thereupon the vestibule contracts as a whole in a typical systole.[24]

As some of the foregoing evidence definitely proves, the circular muscle at the beginning of the pyloric portion is capable of powerfully contracting and completely dividing the gastric lumen. Indeed, in my first observations on the stomach I saw the organ thus divided after I gave the animal apomorphine or mustard to induce vomiting.[25] But what the stomach is *capable* of doing is not proof of normal functioning. Obviously, in my observations unnatural stimulation was employed. Is not the same true also of the other observations supporting the conception of complete separation of the cardiac and pyloric portions? Beaumont admitted that the thermometer tube which he used was an irritant. "If the bulb of the thermometer," he wrote, "be suffered to be drawn down to the pyloric extremity, and retained there for a short time, or if the experiments be repeated too frequently, it causes severe distress, and a sensation like cramp, or spasm, which ceases on withdrawing the tube, but leaves a sense of soreness or tenderness at the pit of the stomach."[26] Perhaps a gastroscope in the stomach might have a similar effect. Even a rubber sound introduced into the human stomach becomes, according to Moritz, a source of irritation.[27] Of course, inferences drawn from study of the excised stomach and from the movements of food seen through a fistula must be standardized by observations made under more natural and more instructive conditions.

I have less hesitation in suggesting that complete division of the stomach at the transverse band is the result of unnatural stimulation because of my own experience. Many times I have carefully watched with the X rays gastric peristalsis in human beings, monkeys, dogs, cats, white rats, and guinea-pigs,[28] and although the waves moving into the pyloric half of the vestibule have at times almost obliterated the lumen, I have never seen such deep constrictions at the beginning of the pyloric portion. The systole of the vestibule in the rabbit I have noted in one instance, but I have also watched in the rabbit's stomach continuous peristalsis, running from the middle of the organ to the pylorus, as in the other animals, without any obliteration of the gastric lumen.

The observation that peristaltic waves run all the way to the pylorus—first reported in May, 1897[29]—was immediately confirmed by the X-ray studies of Roux and Balthazard[30] on frogs, dogs, and human beings. Recently, with greatly improved methods, Kästle, Rieder, and Rosenthal[31] have obtained instantaneous radiographs of the human stomach, and have completely substantiated our early contention that the pyloric end is normally not separated from the rest of the stomach, and that the waves are continued over the vestibule.

The importance of a correct conception of the movements of the pyloric portion lies in its significance for our understanding of the functions of this part of the stomach. If the transverse band completely closes the lumen, and the vestibule then undergoes a systolic contraction, the function of this portion must be mainly one of expelling the food into the duodenum.* On the other hand, if the waves sweep without interruption over this region, deepening as they go, they may have two functions—that of expelling the food, if the pylorus opens; and that of mixing the food with the gastric juice, if the pylorus remains closed. Because observations under normal conditions support the latter conception of the activity of the vestibule, we are warranted in concluding that it has a more important function than that of merely expelling gastric contents into the intestine. After summarizing the description given by Hofmeister and Schutz, Ewald, for *a priori* reasons, declared: "I cannot accept

* Calculation shows that the volume of the two parts of the moderately filled stomach of the dog is such that if at each "diastole" the vestibule were filled, and at each "systole" it forced the contents into the duodenum, the stomach would be emptied within two minutes!

this view. The plain fact that the pyloric portion secretes a strongly digesting fluid . . . proves it to be an important part for the peptonizing function of the stomach."[32] The account of the remarkable manner in which the pyloric portion performs this function must be deferred until we consider the effects of gastric movements on the contained food.

When an animal is examined with the X rays immediately after receiving a meal which fills the stomach, there appears within a brief interval a slight annular constriction near the beginning of the vestibule, which moves slowly to the pylorus. This is followed by several waves recurring at regular intervals in the same region. Two or three minutes later very slight constrictions appear near the middle of the body of the stomach, and, pressing deeper into the greater curvature, course towards the pyloric end. Since the waves are repeated rhythmically, the circumference in which they start must pulsate. And since the time required for the waves to go from the source to the pylorus is longer than the interval between pulsations, several waves are always seen on the stomach at the same time.

When a wave sweeps round the bend into the vestibule, the indentation made by it increases. As digestion proceeds, the constrictions in the region of the vestibule grow still stronger, and finally, when the stomach is almost empty, they may, as they come near the pylorus, completely divide the cavity. At all times, in the close neighbourhood of the pyloric canal, the circular and longitudinal muscles, both of which are here strongly developed, probably co-operate to decrease simultaneously in all directions the terminal segment of the stomach. Certainly there is a fairly quick change from a rounded, bulging mass of food, in front of the advancing ring, to a much smaller mass, just before the wave disappears at the pylorus (compare 2 and 3, Fig. 4).[33]

Gastric peristaltic waves do not pass on to the duodenum, but stop at the pylorus. This separation of the two regions is probably to be accounted for by the interruption in the continuity of the circular fibres just beyond the pyloric sphincter.

The rate of recurrence of the waves varies in different animals. In the cat it ranges from four to six waves per minute ; in the dog the rate is about four per minute ; and in man about three. Age apparently has little influence on the rate. The number of waves per minute in kittens about six weeks old was within

the limits of variation noted in adult animals. Under given conditions the rhythm is remarkably regular. I have many times been able to tell within two or three seconds when a minute has elapsed, simply by observing the undulations as they passed a selected point.

A slower recurrence of the gastric waves when fat was fed than when bread-and-milk mush was fed suggested that there might be characteristic rates for different foodstuffs. Observations at different intervals after feeding different foods gave the following results :[34]

	Number of Observations.	Average Rate per Minute.	Most Frequent Rate.	Extreme Variations.
Fats	23	5·0	5·2	4 to 6
Proteins	16	5·2	5 to 5·4	4·8 ,, 5·8
Carbohydrates ..	13	5·5	5·8	5 ,, 6

The average rate of peristalsis increases from fats to proteins and from proteins to carbohydrates, and the rate most frequently observed varies in the same direction; but the differences are so slight and the variation with any given food so great as to make it improbable that each foodstuff produces a characteristic rate.

As a result of my first observations on the stomach, I stated that in normal conditions gastric peristaltic waves are continuously running, so long as food remains in the organ.[35] Hundreds of observations made since that time on various animals—mainly on cats, but also on dogs, guinea-pigs, and white rats—as well as records from human beings,[36] have confirmed the conclusion that peristalsis continues uninterruptedly until the stomach is swept clear of its contents.* The number of waves during a single period of digestion is larger than might at first be supposed. In a cat that finished eating, at 10.52 a.m., 15 grammes of bread, the waves were running regularly at eleven o'clock. The stomach, examined and found active every half-hour, was not empty until after six o'clock. At the average rate for carbohydrate food (5·5 waves per minute), approximately 2,300 waves passed to the pylorus during that single digestive period. When proteins or fats are fed, the stomach is emptied more slowly than when equal amounts of carbohydrates are fed.[37] Although the average rate of gastric peristalsis, as

* The rabbit offers an exception to this general statement.

we have seen, is slower for proteins and fats than for carbohydrates, the differences are so slight that the slower rate does not compensate for the longer residence in the stomach. When equal amounts of protein, fat, or carbohydrate, are fed, therefore, a much larger number of peristaltic waves, and consequently a much greater expenditure of energy in the contraction of gastric muscle, is required by the proteins and fats than by the carbohydrates, before the stomach is emptied.

In some animals I have watched, the waves were repeated less frequently as gastric digestion proceeded; but records made at intervals during seven hours, after feeding different foods, showed no constant direction of variation. No general statement, therefore, regarding the tendency of the waves to vary in rate as the stomach is being evacuated, can safely be ventured.

The condition for the appearance of gastric peristalsis has received relatively little attention. According to Edelmann, who studied the stomach by means of a balloon introduced into the organ, the movements are temporally related to the secretion of gastric juice. Furthermore, he states that neutralization or dilution of the gastric juice results in cessation of the movements, which are restored only when the contents become again strongly acid.[38] In the experiments of Hedblom and myself, the feeding of acid food was attended by especially deep and rapid peristaltic waves; the rate was usually slightly faster than six waves per minute.[39] And the feeding of fatty food, which inhibits gastric secretion, was in my experience usually attended by relatively shallow gastric waves.[40] Although there is this evidence of concomitant variation of acid gastric contents and peristalsis, it is not proof that the waves are the result of an acid stimulation. Indeed, I have observed deep and strong peristaltic waves in the stomach when the contents were strongly alkaline.[41] And, furthermore, peristalsis starts *immediately*, when food is introduced into an empty stomach, if only the organ is at the time in a state of tonic contraction. The secretion of gastric juice does not occur with such promptness. The causal relation does not exist, I believe, between secretion and peristalsis but between these two and a common antecedent factor. A discussion of this matter must, however, be deferred until later.

A modification of the normal movements of the stomach is seen when vomiting occurs. Vomiting can be induced by irritation of the gastric mucosa, or by stimulation of centres in the

medulla, or, as Valenti has recently shown, by the excitation of a well-defined region between the pharynx and the top of the œsophagus.[42] The centrifugal impulses pass through the vagi, dilating the cardia. These impulses also cause dilation of the cardiac end of the stomach, while increasing the tonus of the pyloric region. X-ray observations on cats given apomorphine subcutaneously, or mustard by stomach-tube,[43] correspond closely with Openchowski's description of the appearances of the exposed stomach during emesis. The first change is the total inhibition of the cardiac end of the stomach, which becomes a perfectly flaccid bag. This is followed, when apomorphine has been given, by several deep contractions that sweep from the mid-region of the organ towards the pylorus, each of which stops as a deep ring at the beginning of the vestibule, while a slighter wave continues. Finally, in all cases, a strong contraction at the angular incisure completely divides the gastric cavity into two parts. Although waves continue running over the vestibule, the body of the stomach and the cardiac sac are fully relaxed. Now a simultaneous jerk of the diaphragm and the muscles of the abdominal wall shoots the contents out through the relaxed cardia. As these jerks are repeated, the gastric wall seems to tighten around the remnant of contents. Once during emesis I saw an antiperistaltic constriction start at the pylorus and run back over the vestibule, completely obliterating the cavity, but stopping at the angular incisure. In the process of ridding the gastric mucosa of irritants, therefore, the stomach plays a relatively passive rôle.

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CHAPTER VI

THE EFFECTS OF STOMACH MOVEMENTS ON THE CONTENTS

WHATEVER the amount of food sent to the stomach, the organ has a wonderful ability to adapt itself with precision to the volume of the contents. Even during the short time of a single digestive period the body of the stomach may contract from a large conical sac, many centimetres in circumference, to a narrow tube little larger than a loop of intestine. Furthermore, during this alteration in size the pressure remains practically uniform. The change in the opposite direction, from smaller to larger capacity, Kelling[1] proved could occur within a minute or two without noteworthy increase of intragastric pressure. Thus, when he introduced into the stomach of a dog 240 c.c. of material, the pressure was 7·6 centimetres of water ; and when this amount was increased to 460 c.c., the pressure was only 7 centimetres. Since he failed to find persistence of pressure regulation in deep anæsthesia, Kelling inferred that it was a reflex adaptation. More recently, Sick and Tedesko[2] have proved, however, that the excised stomach, kept alive in warm oxygenated Ringer's solution, is able to adapt itself to increase of volume by an intrinsic relaxation, especially in the cardiac end, so that there is no marked increase of pressure. Observations which I have made on cats entirely confirm the results of both Kelling and Sick ; and I have also seen the excised stomach gradually contract, as the contents were decreased, and maintain continuously the pressure that existed before the decrease. The mechanism by which the stomach becomes so remarkably adjusted to its contained volume may exist, therefore, within itself.

The nature of the adjustment in the stomach wall is not yet clearly explained. Mere relaxation of the tonic contraction of the gastric muscle, according to Grützner, would not account

for the great changes in the capacity of the stomach without attendant alterations of intragastric pressure.[3] Müller,[4] working under Grützner's direction, compared the relaxed muscle fibres in the full stomach and the contracted fibres in the empty stomach of the frog and salamander. He found that, whereas the length of the relaxed fibres was not more than three times that of the contracted, the circumference of the full stomach was five times that of the empty. The discrepancy he explained as due to a rearrangement of the fibres: the musculature of the full stomach was composed of only two or three layers of fibres, while the contracted stomach had from fifteen to twenty layers. How the fibres can thus slip by one another and still maintain continuous pressure, and how, once dissociated, they are restored to the multiplex composition of the contracted state is not explained.

Another adjustment required by the filling of the stomach is that of the abdominal muscles to the enlargement of the abdominal contents. According to Kelling, the abdominal contents of the dog may be increased 100 per cent. by a single meal. Obviously, if the muscles of the abdominal wall do not relax, intra-abdominal pressure must increase—a result which might produce serious circulatory disturbances. As the stomach is filled, however, the muscles are relaxed, and in consequence the pressure within the abdomen is not affected by taking food. Apparently this adaptation of the abdominal muscles is a reflex originated in the stomach or intestines; for when air or salt solution is injected into the peritoneal cavity, the pressure is at once increased.[5]

The figures given for intragastric pressure vary somewhat with different observers, and, as might be expected, the pressures are different in the less active cardiac end, holding the food in tonic grasp, and in the more active pyloric end, undergoing repeated compression by peristaltic waves. We have already learned that these waves, as they move along the pyloric vestibule, press gradually deeper into the contents. The pressure, therefore, should be greater at the pylorus than elsewhere in the stomach. Actual measurement of the pressure in the cardiac and pyloric ends of the human stomach have been made. Von Pfungen introduced into the stomach of a boy who had a gastric fistula 8 centimetres to the left of the mid-line a rubber balloon, and found that intragastric pressure near the fistula was upward from

19 centimetres of water, whereas directly in front of the pylorus the pressure was 162 centimetres of water.[6] By means of an intragastric bag passed down the œsophagus, Moritz studied the pressures in the two ends of the stomach in a normal individual. Although his figures are lower than v. Pfungen's, they show a similar difference between the cardiac and pyloric portions. The usual pressure in the cardiac end varied between 6 and 8 centimetres of water, while in the pyloric end there were rhythmic recurrences of pressure amounting in some instances to 38, 40, and even 60 centimetres of water, though as a rule ranging from 20 to 30 centimetres.[7] The results obtained by Sick, who used the method of Moritz, were confirmatory—7 to 16 centimetres pressure in the cardiac end, contrasted with 25 to 42 centimetres in the pyloric end.[8]

The methods used in these experiments are not above criticism. The presence of the experimenter's tube, especially in the pyloric vestibule, where deepening peristaltic constrictions narrow the lumen, may have prevented to some extent a free movement of the contents, and may have thus unnaturally increased the pressure in that region. Also the balloon may have stimulated unusually strong contractions in the pyloric portion, and in that way increased the difference between the pressures in the two ends of the stomach. Yet the results obtained are what might be expected from greater depth of the constrictions as they approach the pylorus, and this concurrent evidence distinctly indicates that towards the pyloric exit the intragastric pressure becomes considerably greater than it is near the less active fundus. This conclusion is confirmed by the manner in which chyme is discharged into the duodenum. In my X-ray observations, whenever the chyme was permitted to emerge, I saw it spurted through the pylorus and shot along the intestine for several centimetres. The same testimony to the efficacy of pressure at the pylorus is given by investigators who have watched the gastric discharge through a duodenal fistula.

The absence of peristalsis over the cardiac sac, and the presence of gradually deepening peristaltic constrictions in the pyloric vestibule, have important practical consequences. Before considering them, however, we shall review what is known of the effects of gastric movements on the contents of these two parts of the stomach.

A difference in the activities of the two ends of the stomach

might have been inferred from old observations on the appearance of the food in the cardiac and pyloric portions. In 1814, Home described two parts of the stomach of the dog, " that next the cardia the largest, and usually containing a quantity of liquid in which there was solid food, but the other, which extended to the pylorus, being filled entirely with half-digested food of a uniform consistence."[9] Twenty years later Eberle reported that, when the stomach of a dog is carefully opened during digestion, the surface of the mass in the cardiac end shows signs of digestion, but the interior of the mass remains unchanged, whereas the contents of the pyloric end are throughout uniformly mushy and fluid.[10] Many years later, Ellenberger and his students demonstrated that, for several hours after eating, the digestive processes in the two ends of the stomach of the horse and the pig were quite different, and that different foods fed successively were found, not uniformly mixed, but arranged in strata.[11]

These excellent observations were for a long time obscured by Beaumont's description of the circulation of the food in the human stomach, a description so circumstantial and detailed as to present all the semblance of exactness. " The bolus as it enters the cardia," Beaumont wrote, " turns to the left; passes the aperture; descends into the splenic extremity; and follows the great curvature towards the pyloric end. It then returns, in the course of the small curvature, makes its appearance again at the aperture, in its descent into the great curvature, to perform similar revolutions."[12] That Beaumont's conclusions were based on the movements of a thermometer tube introduced through a fistula, and on the appearance of particles of food in the gastric contents as they passed the fistulous opening, was not criticized. Yet, as we now know, the irritation by the thermometer tube produced abnormal contractions, and the course which the particles took when out of the observer's sight could not be fairly judged.

It is easily possible to test experimentally the validity of Beaumont's inferences by watching with the X rays the movements of pieces of food prepared to throw a black shadow in a dimly outlined stomach. For this purpose I made little paste pellets of bismuth subnitrate, with starch enough to preserve the form, and gave them with the customary food, containing relatively much less of the bismuth salt. These pellets, when

partly dried, did not disintegrate in the stomach during the gastric digestion of soft bread. Several times I was fortunate in finding two of the little balls in the axis of the body of the stomach, and about a centimetre apart. As a constriction wave approached them, both moved forward, but not so rapidly as the wave. Now, when the constriction overtook the first ball, the ball moved back towards the fundus through the moving constricted ring, in the direction of least resistance. The wave then overtook the second ball, and it also passed backward to join its fellow. At the approach of the next wave they were both pushed forward once more, only to be again forced backward, one at a time, through the narrow orifice. But as the waves recurred in their persistent rhythm, the balls were seen to be making progress—an oscillating progress—towards the pylorus; for they went forward each time a little farther than they retreated. This to-and-fro movement of the pellets was in no way interrupted in the region of the transverse band, which is additiona good evidence that normally it does not divide the stomach into two parts. In the pyloric vestibule, where the peristaltic waves were deep, the oscillations were more marked than in the body of the stomach. On different occasions from nine to twelve minutes elapsed while the balls were being pushed from where the waves first affected them to the pylorus; on the way, therefore, they must have been churned back and forth by approximately a half-hundred constrictions.[13]

In the cardiac sac no signs of currents were visible. Balls which lay in this region immediately after the food was ingested kept their relative positions until the sac began to contract, and then moved slowly towards the pyloric end. The immobility of the food in the cardiac sac was also proved by feeding first 5 grammes of bread and bismuth subnitrate, then 5 grammes of bread alone, and finally 5 grammes of bread with the bismuth salt again. The first stratum lay along the greater curvature and extended into the pyloric vestibule, the third stratum spread along the lesser curvature, and the second rested between. Tracings of this stratification of the contents were made on transparent paper. Ten minutes after peristalsis began, the stratification had entirely disappeared towards the pyloric end of the stomach, but in the cardiac end, after an hour and twenty minutes, the layers were still clearly visible.[14]

These X-ray observations on the stratification of the gastric

contents are in fair agreement with the observations of Ellenberger and Goldschmidt on the horse, which have since been confirmed by Scheunert.[15] They do not present the arrangement so uniformly simple as Grützner has described it.[16] He fed in succession foods differently coloured, and, after digestion had continued for an hour or more, killed the animal, froze the stomach with its contents, and then made sections of it. Frogs and toads, rats, cats, and dogs, served as subjects for the investigation. As in the X-ray experiments, he reports that the first food was pushed along the greater curvature by the later masses, but it was also spread outwards from the greater curvature, in the form of a thin layer, which prevented the later masses, lying within, from coming into direct contact with the secreting mucosa. Thus, whenever new food was given, it nested in the midst of the food already present, just as described by Eberle in 1834. In the pyloric end, Grützner found that after digestion began the strata soon became broken and warped.

Direct study of the motions of the food in the stomach, therefore, wholly discredits the account given by Beaumont; not even when the contents are fluid does circulation occur. On the other hand, the motions observed offer a complete explanation of the difference in the gastric contents at the two ends of the stomach as described by Home and Eberle. Anyone can readily verify the basic observation which first indicated the separate functions of the cardiac and pyloric ends. The food in the centre of the cardiac sac has the same appearance after an hour and a half of gastric peristalsis that it had when ingested, but the contents of the pyloric vestibule, which the waves have been churning, are changed to the consistency of thick soup.

The absence of any motions in the contents of the cardiac sac suggested that the food during its stay there has little opportunity to become mixed with the gastric juice, and thus to undergo peptic digestion. The truth of this supposition was easily proved experimentally by feeding a slightly alkaline food, and later testing the reaction of the contents in various parts of the stomach.

A cat which had been without food for fifteen hours was given 18 grammes of mushy bread made slightly alkaline with sodium carbonate. One hour and a half after the cat had finished eating she was killed, and the stomach exposed by opening the abdomen. A very small hole was then made in the wall of the cardiac sac,

nd another similar hole was made in the pyloric vestibule. By means of a glass pipette food was extracted first from the periphery of the cardiac sac; this food was slightly acid. The cleaned pipette was then introduced 2·5 centimetres into the contents of the sac; the food thus extracted gave the original alkaline reaction. Specimens of the fluid contents near the pyloric end, taken from various depths, were all strongly acid.[17]

These observations on the cat I repeated on the dog. They have been completely confirmed by Heyde working with Grützner. Rats, rabbits, guinea-pigs, and cats, were fed by Heyde with different kinds of food mixed with acid indicators, and were killed at different intervals after eating. The stomachs were carefully removed and frozen; sections were made through the frozen contents, and the altered colour of the indicators revealed at once the extent of acidification. The inner layers of the food in the cardiac end retained for hours a neutral or weakly alkaline reaction; only the outer layers were slightly acidified and digested.[18]

As we have already learned, the functional difference between the cardiac and pyloric ends of the stomach is the same in man as in the dog, the cat, and other experimental animals. Does a corresponding difference prevail between the character of the contents in the two ends of the human stomach? Does the mass of food in the quiet cardiac sac remain long unmixed with gastric juice while that in the pyloric end is intimately churned by the peristaltic waves? These questions have been considered by Sick,[19] who, using a specially-devised stomach-tube, removed samples of the contents from the cardiac or pyloric end at will. The subjects took a semi-fluid test-meal, and then swallowed a cachet containing carmine or charcoal. After a given time the stomach-tube was introduced, first into the pyloric, and later into the cardiac end. In spite of the semi-fluid gastric contents, and in spite of exercise by the subjects during the interval of digestion, the pyloric part of the stomach remained wholly free from the colouring material for fifteen or twenty minutes—indeed, in some cases for almost twenty-five minutes—while the cachet had meanwhile dissolved and liberated its contents into the food of the cardiac end. Gradually, after thirty or forty minutes, the carmine powder appeared near the pylorus. Sick also found a difference in the consistency of the contents in the two portions of the stomach: in the pyloric end a thin fluid was present,

homogeneous in character; in the cardiac end a lumpy, rather coherent mass. He concluded, therefore, that in the human stomach, even when the food is somewhat fluid, an important difference exists between the physical and chemical nature of the contents of the two ends, and that only slowly does a complete mixture take place. This conclusion is supported by the experiments of Prym,[20] who has furthermore emphasized the significance of this differential treatment of the food for the clinical examination of gastric contents. Evidently, if the contents are not a uniform and homogeneous mixture, not only may the stomach-tube give wrong testimony regarding the conditions in the organ, but the food even when expressed as a whole may be equally deceptive.

The application to man of the facts determined for animals has been criticized by Hertz, who has declared that gas in the fundus of the human stomach (gas is practically always present) causes the œsophagus to discharge new food either on or slightly below the upper surface of the stomach contents, and thus not into the centre of the mass in the cardiac sac. He has also suggested that the delay in the appearance of the colouring materials (carmine and charcoal) in the pyloric end, noted by Sick, was due to their first floating on the surface of the contents, whence they could become only gradually incorporated.[21] Of course the question of the stratification of the food is really not involved in a consideration of the mechanical effects of peristalsis in one end of the stomach, and mere tonic contraction in the other end. Hertz seems not to have given due weight to the statement of Sick that about three-fourths of his subjects were reclining on the right side, nor has he offered any explanation of the difference in the consistency of the food from the two parts of the stomach, which Sick reported. Certainly the greater size of the human stomach does not cause it to act differently on the food than do the stomachs of dogs and cats, for, as already stated, Ellenberger and Goldschmidt proved that there was no general mixture of the gastric contents in the horse during several hours after the ingestion of food. The main argument of Hertz seems to be based on the assumption that gastric contents are so fluid as to be the medium of rapid diffusion. Experiments to be described later show that diffusion does indeed occur even in viscous gastric contents, and that when the contents are of a thin, fluid consistency the diffusion may

be rapid. After an ordinary generous meal, however, with a satisfactory variety of food, the gastric contents, as the autopsy-room demonstrates, may not be fluid, but a thick and mushy mass. In such a mass diffusion currents must be slow. Indeed, the currents described by Beaumont, resulting from the movements of the gastric wall, could hardly occur. Under such circumstances, therefore, the evidence points to the same effects on the food in the two ends of the human stomach as are found in animals.

The supposed value of the circulation of the food in currents running throughout the stomach, as described by Beaumont, lay in the means it offered for bringing the contents of the stomach near to the secreting gastric mucosa, and thus permitting the gastric juice to exert more readily its action. Although my X-ray observations did not support Beaumont's description of a mixing current moving along the greater and lesser curvatures, they nevertheless showed that in the pyloric vestibule and the region just before it an admirable mechanism exists for bringing all of the food into intimate contact with the mucosa in that region. Evidently, when a constriction occurs, the mucous surface enclosed by the ring is brought close around a narrow isthmus of food or chyme lying in the axis of the stomach. Now, as this constriction passes on, fresh areas of the mucosa are continuously pressed inward to form the little orifice. And at the same time, as the constriction moves, a thin stream of the gastric contents is continuously forced back through the orifice. The result of this admirable mechanism, indicated by the oscillating pellets, is that every part of the mucosa of the pyloric portion is brought near to every bit of food a large number of times before the food leaves the stomach.

It is well known that the mucosa of the pyloric portion of the stomach does not secrete hydrochloric acid, although it does secrete pepsin. Yet the contents of this region, all observers agree, become uniformly acid in reaction soon after gastric digestion begins, and remain thus until the stomach is emptied. We must assume, therefore, that the acid-pepsin secretion is pressed onward from the surface of the contents of the cardiac portion, by the gentle waves of peristalsis in that region, and gradually mixed into the contents of the vestibule. Meanwhile, however, the deep waves approaching the pylorus have churned the vestibular food with the local pepsin secretion, and now,

as the imported acid appears, proteolytic digestion can progress rapidly.[22] Thorough mixture of the food with the secretion of the vestibule and with the gastric juice from the body of the stomach is therefore one of the functions of the peristaltic waves. The resulting chyme is a soupy, homogeneous fluid, ready for exit into the intestine.

Another function of the intimate contact of mucosa with gastric contents in the pyloric region is that of continuing gastric secretion. As Edkin's experiments proved, the condition for the continued secretion of gastric juice, after the initial "psychic" secretion, lies in a chemical stimulation of the gland cells through the blood-stream.[23] The chemical stimulant given to the blood is produced, not by the mucosa of the cardiac end of the stomach, but by that of the pyloric end. And the vestibular mucosa is roused to activity by the presence of acid, peptone, or sugar solutions—a presence which is repeatedly forced on the mucosa by the churning waves.

An associated function of the churning action in the vestibule is concerned with absorption. Although water is not absorbed in the stomach, glucose in concentrated solution, and proteins which have been exposed to gastric digestion, may be absorbed in considerable amount.[24] The mucosa of the vestibule has many fewer glands than the mucosa of the cardiac end, where they are placed in very close order. The absorption that occurs in the stomach, therefore, probably takes place in the vestibule, for there the epithelial surface is most favourable to the process. There also gastric digestion is most advanced, and the food in consequence is most ready for passage through the mucosa. And, furthermore, in the vestibule the mechanical conditions are most favourable to absorption, because the digested food is repeatedly brought into very close contact with the mucous lining.

If the pylorus does not relax before an approaching wave, the food is pressed into a blind contractile pouch, the only exit from which is backward through the advancing ring of constriction. As we have seen, the constrictions are deeper near the pylorus, and the rings therefore are small; consequently the food is squirted backward through them with considerable violence. The action of this part of the stomach on the food can be observed by means of the little pellets which I have already mentioned. As the slow waves push the little morsel and the surrounding soft food up to the closed sphincter, the whole mass is squirted back

into the vestibule. Again and again I have seen this process repeated until the sphincter relaxed and allowed the more fluid parts to pass out.*

The older writers on the physiology of digestion described a selective action of the pylorus. The region of the sphincter was supposed to possess a peculiar sensitivity which caused it to prevent the passage of undigested material into the duodenum. Hofmeister and Schutz, and Moritz, have disclaimed any such function, and have declared that solid particles are carried from near the exit of the stomach back to the cardiac end by antiperistaltic waves. The action at the pylorus which I have seen, however, was like that described by the older writers; for during digestion there was no antiperistalsis, and the sphincter, separating the fluids from the solids, as in the case of the hard morsels mentioned above, caused the solids to remain and undergo a tireless rubbing. Frequently, when several of these pellets were given at the same time, they have all been seen in the vestibule after the stomach was otherwise empty. There they remained, to be softened in time by the digestive juices or to be forced through the pylorus later, for, as is well known, solids do pass into the intestine.[25] It seems highly probable that the prevalence of pathological conditions in the pyloric end of the stomach, rather than in the cardiac end, is due to the injury which the greater activity of the pyloric end may bring upon itself.

The presence of peristaltic waves on the right half of the stomach and their absence from the left half indicates two separate parts of the stomach. The evidence now before us shows that these two parts have distinct functions. The left half is a reservoir in which the food is not mixed with the gastric secretion, and from which the contents are slowly pressed out into the active right half. The peristaltic waves coursing over the right half mix the food with the gastric juice, expose it to the mucosa of the vestibule for absorption and for the continuance of gastric secretion, churn the unbroken particles of food until they are triturated, and finally expel the chyme into the duodenum. Still other consequences of the different activities of the two ends of the stomach are next to be considered.

* At a meeting of the Boston Society of Medical Sciences, May 20, 1902, I demonstrated a method of showing the churning function of the stomach, and the activities of other parts of the alimentary canal, by means of the zoetrope.

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CHAPTER VII

THE STOMACH MOVEMENTS IN RELATION TO SALIVARY DIGESTION, AND GASTRO-ENTEROSTOMY

THE discussion of the events in the stomach has thus far shown that the contents may rest in the cardiac end for an hour or more, exposed to a relatively slight pressure, and unaffected by the peristalsis of the pyloric end; and, on the other hand, that the contents of the pyloric end, repeatedly swept to and fro by the passing waves, are repeatedly exposed to a pressure which increases as the pylorus is approached. These conditions have important bearings on the question of salivary digestion in the stomach, and on the course taken by the food after the operation of gastro-enterostomy. These matters we shall now consider.

SALIVARY DIGESTION IN THE STOMACH.

In stating the functions of saliva, emphasis has been laid on its effects as a lubricant for the tongue, cheeks, and lips, and for the food about to be sent through the œsophagus; and as a diluent for irritating substances taken into the mouth. Saliva can indeed change starch to sugar; but during ordinary mastication the short time for this chemical change has been pointed out, and in the stomach the action of ptyalin has been supposed to be soon stopped by the acid gastric juice.

The short time assumed for salivary digestion in the stomach was supported by Beaumont's conception that all the food was rapidly acidified by circulation along the gastric walls. These mixing currents, however, as we have seen, do not exist, and in the cardiac end, although the surface of the contents becomes acid, the internal mass of the contents remains unchanged in reaction. Since salivary digestion can continue so long as free acid is absent, I suggested in 1898 that salivary digestion might

proceed in the cardiac sac for an hour or more without interference by the acid gastric juice.[1] This conclusion has been supported by Oehl,[2] and by Heyde, whose experimental work with Grützner has been described.

Several researches have been published indicating the possibility of rather extensive amylolysis in man. As long ago as 1880, von den Velden pointed out that free hydrochloric acid does not appear for almost an hour after eating an ordinary breakfast, and for almost two hours after eating a full midday meal. And, later, Hensay[3] and Müller,[4] presented quantitative analyses of the amounts of sugar and dextrins which might be formed in the stomach when food is carefully chewed. They found that after a half-hour in the stomach carbohydrate food was in large part made soluble by saliva, that over one-half, even two-thirds, of the soluble portion consisted of maltose and of dextrins closely related to maltose, and that the remainder consisted of dextrins more nearly related to starch.

None of the observers who brought forward these positive results regarded the differences between the pyloric and cardiac ends of the stomach. To be sure, many years ago Ellenberger and Hofmeister had studied the digestive processes in the pyloric vestibule and the cardiac sac of the horse and pig,[5] and later Hohmeier reported similar studies on the rat.[6] The cardiac end of the stomach in the horse, pig, and rat, however, is to a great extent lined with inactive pavement epithelium, and with " cardia " glands, the secretion of which is not acid.[7] A demonstration of salivary digestion in the cardiac end of the stomach under these circumstances is not satisfactory proof of what occurs in animals in which the secretion of the cardiac wall is strongly acid. H. F. Day and I[8] undertook, therefore, an investigation of salivary digestion in the stomach of the cat, which resembles the stomach of the dog and of man, not only in structure, but also in pouring out an active secretion from almost every part of its surface.

Crackers, free from sugar, were powdered, weighed in uniform amount (30 grammes), and mixed with a uniform volume of filtered human saliva (100 c.c.). The resulting thick mush was immediately fed in small amounts or introduced by a tube into the stomach of the hungry animal. At the end of a half-hour, an hour, one and a half or two hours, the animals were quickly etherized, and the stomach excised, after the contents

of the pyloric and cardiac ends had been separated by a ligature tied around midway between them. The contents of the two ends were at once removed, and the enzyme action stopped by boiling. After the food had evaporated to dryness, it was powdered, 1 gramme of it was mixed with 100 c.c. of distilled water, the mixture was allowed to stand for a half-hour, then filtered, and the filtrate tested for sugar (as maltose) by Allihn's method.

Two factors, besides the difference between the two ends of the stomach, had to be considered. One was the rapidity of salivary digestion. Starchy foods vary considerably among themselves in the rate at which they change to sugar.[9] The material used by us was tested *in vitro* at 38° C., and in seven minutes four-fifths of the amount of sugar found at the end of an hour was already present. Under these conditions the accumulation of the products of digestion inhibited the action of the ferment as time passed; nevertheless, the change was clearly of sufficient rapidity to result in considerable amylolysis before being checked by acid, even in the pyloric end. The second condition to be considered was the possibility of any agency, except saliva, that would change starch to sugar. Control experiments, in which the powdered cracker was mixed with distilled water, revealed only the slightest trace of any reducing action.

Our examination showed that after a half-hour the contents of the cardiac and the pyloric ends of the stomach have about the same percentage of sugar, and that after an hour the cardiac mass, because of continued amylolysis, contains about 80 per cent. more sugar, in unit volumes, than the vestibular mass. The difference is doubtless actually greater, for the food in the cardiac end is drier than that in the pyloric end, and we examined the dried material. From an hour to two hours after feeding, the ratio of the sugar percentages in the two parts of the stomach begins to approximate unity again. This change is probably due largely to diffusion of the sugar solution from the cardiac to the pyloric contents. The possibility of this diffusion was proved by feeding first salmon and later crackers mixed with saliva. At the end of an hour some of the salmon taken from near the surface in the cardiac end, fully 1·5 centimetres from the stratum of crackers, contained 3 per cent. as much sugar as the crackers. This diffusion, however, did not, in our experiments, remove to any important degree the ptyalin

from the mass in the cardiac sac, nor did the position of the stomach affect the differences in sugar production in the two parts.

When liquid food was given, and when small amounts of food were given, the sugar percentages in the two parts of the stomach were nearly the same. This observation, probably explicable on the basis of ready diffusion, or uniform penetration of the acid gastric juice, has important bearings, for it indicates that the usual test-meal, small in volume and containing fluid, becomes homogeneous in the two parts of the stomach, and that therefore any part of it, which is taken for examination, is very like any other part.

Much of the starch which was not changed to sugar was changed to dextrin, and thus, since dextrin is not readily fermented, the food was possibly saved to the organism. The especial value of this process lies in its occurrence in greatest degree in the midst of the cardiac contents, where hydrochloric acid, which inhibits the action of many of the organized ferments, does not for some time make its appearance.

We may conclude therefore that, in the early stages of gastric digestion, after an ordinarily bountiful meal which has been properly masticated, the contents of the cardiac end of the stomach, although undergoing proteolysis on the surface, are chiefly subject to the action of ptyalin ; and, furthermore, that the contents of the pyloric end, after a brief stage of salivary digestion, are subject thereafter to strictly peptic changes. Later, as the contents of the fundus become acid, the food in the stomach as a whole receives uniform treatment.

The observations of Müller and Hensay on salivary digestion in man, together with the results obtained by Day and myself, emphasize again the importance of mastication. A large portion of the food consists of starch. Only by mastication is this food properly broken up so that a large surface is exposed to the action of ptyalin. When it has been thus thoroughly insalivated, it will go far on the way to final digestion, while waiting to be discharged from the stomach.

The Movement of Food after Gastro-Enterostomy.

If the pyloric canal becomes narrow or closed, or if there is otherwise delay in the passage of food from the stomach, the common operation of making an artificial anastomosis, or *stoma*,

between the stomach and a loop of small intestine is performed, in order to render the forwarding of the gastric contents possible or more rapid. The assumption is that always after gastro-enterostomy there is a change in the course which the food takes in going from the stomach into the bowel. Two questions of interest arise with regard to the effect of the new opening. Under what conditions does it induce an alteration in the normal course of the food? And if the normal course of the food is changed, what are the results?

In much of the surgical literature on gastro-enterostomy, until within a few years, the operation was conceived as a "drainage" operation, and surgeons were careful to make the stoma at the most dependent point in the stomach. Involved in this conception are the assumptions that the stomach is a relatively passive bag, and that the food, swallowed in a semi-solid state, somehow becomes liquid, and by gravity runs through the new hole into the intestine. Facts which we have already considered prevent us from giving ready credence to these assumptions.

The stomach is not at any time during digestion in the condition of a passive reservoir; the cardiac end is exerting a positive pressure, and, so long as food is present, the pyloric end is the seat of continuous peristalsis. The statement has been made repeatedly in surgical writings, that a gastro-enterostomy midway in the stomach relieves the pylorus of the irritation from food and gastric juices. It seems to be assumed that the region between the new opening and the pylorus becomes unnecessary for digestion, and inactive. There is no reason, however, for believing that peristalsis does not persist under these circumstances, and that the food is not thoroughly churned in the pyloric end in the normal manner. Although, in cases of pyloric stenosis, gastro-enterostomy, of course, shortens the time during which peristalsis and acid juices are present in the pyloric end of the stomach, we should not deceive ourselves by the supposition that the operation permits this region to enjoy entire relief from either of these disturbing conditions. In observations on animals in which the stomach and gut had been artificially joined, and the pylorus externally ligated or completely closed by sutures, I have seen the waves passing over the pyloric end without interruption for long periods.

Our previous consideration has shown that, as the stomach empties, the most dependent point changes its position. The

greater curvature of the relaxed or full stomach may indeed reach considerably below the pylorus, but as the contents disappear, the greater curvature rises, and the pylorus, being more or less fixed, then becomes the lowest point.

The argument may be advanced that observations on a normal animal do not hold good for abnormal conditions in human beings. The claim may be made that the attachment of the intestine to the stomach acts as a drag, keeping the stoma at the most dependent point, and that then the stomach must be merely a passive reservoir with its contents drained by gravity. Or the point may be urged that when the stomach is dilated, toneless, and flabby, it cannot act normally, and that the part observed to be lowest when the abdomen is opened must remain so.

In this connection the ready mobility of the intestinal coils may be mentioned. If the stomach, however, has been purposely attached to a *fixed* portion of the gut in order to make the stoma permanently the most dependent point, or even if the new opening remains lowest because of pathological conditions, we may reasonably question whether evacuation is thereby facilitated. For in our discussion of the doctrinaire notions of the shape of the normal stomach we learned that the hydrostatic conditions in the abdominal cavity are such that gravity drainage is impossible — that when a gastro-enterostomized stomach is filled with water the water does not run out by itself, even with the subject in the upright position. In other words, material does not move along the alimentary canal unless the pressure is greater on one side of it than on the other.

What we have learned regarding the pressure relations in the stomach is pertinent to the present discussion. As we have seen, peristaltic waves are continuously passing over the pyloric end so long as food is present, and on approaching the sphincter they become deeper and deeper until they almost obliterate the lumen. Two results follow from this peristaltic activity. The waves which force the food repeatedly against a closed pylorus mix the food with the gastric juice, and churn the mixture into a fluid chyme. The first effect of the waves, therefore, is to render the contents of the pyloric end of the stomach more liquid, and therefore more freely movable than the contents of the cardiac end. The second effect of the gradually deepening waves is that the pressure within the stomach is greater near the pylorus than anywhere else.

The direct consequence of greater fluidity of food near the pylorus and greater pressure on the food at that point is that the chyme takes its normal passage through the pylorus, if the pylorus is patent, rather than through any artificial opening. This fact was first determined by Kelling, who performed gastro-enterostomies on dogs by all the methods known to surgery—on the anterior and posterior surfaces of the stomach, with high attachment of the jejunum, with low attachment of the jejunum, by union with the ileum at any part—and at the same time made a duodenal fistula. He observed that nothing left by the stoma, as could be determined through the duodenal fistula; all food, whether solid or liquid, emerged from the stomach by way of the pylorus.[10] This observation was confirmed in X-ray studies by J. B. Blake and myself.[11] We made openings of various sizes and at various positions between the stomach and intestine. When fluid boiled starch was given, this fluid, instead of running through the stoma into the intestine, was forced out naturally through the pylorus. Only two exceptions were observed in our experience: one in an animal with the stoma on the posterior wall of the vestibule close to the pylorus, and the other in an animal with a large anterior stoma (3 centimetres long) about halfway between the two ends of the stomach. The food left by both exits; but in the latter case salmon, less fluid, went out by the pylorus alone. It was not observed passing through the stoma at any time during four and a half hours after feeding.

In one instance the pylorus was partly occluded. A tape was passed through the walls of the stomach in front of the pylorus and tied; then the gastric wall was sewed tightly over the entrance and exit of the tape. The food still passed out through the pylorus. In another instance a linen ligature was tied snugly around the canal at the pyloric sphincter. A week later liquid boiled starch was fed, and, although peristaltic waves were continually pressing up to the pylorus, the food was seen passing out wholly by way of the stoma. Still later, when thick salmon was fed, the stomach was watched for the first three-quarters of an hour, and again between two and two and a half hours after the feeding. No food was observed going from the stoma, but in small amounts it was passing through the pylorus. At autopsy the ligature was found partially embedded, and the pyloric opening was about 0·3 centimetre

in diameter. These cases clearly show that even when the pylorus is narrowed so as to make difficult the passage of the chyme, the chyme is forced into the intestine by the natural way rather than through an opening remote from the greatest pressure.

When salmon was fed, the food, with the one exception above mentioned, was never seen leaving the stomach by the artificial opening, if the pylorus was patent. The salmon, as a more solid food than the starch paste, becomes, as we have seen, fluid near the pylorus, although remaining in its swallowed condition in the cardiac end. Naturally, a more fluid material under general pressure should pass more readily through an opening in the stomach than a drier and more solid mass. For this reason alone the chyme should go out through the pylorus sooner than the unchymified food through an opening in the middle of the stomach. And when this difference of consistency, favourable to the pyloric passage, is combined with greater pressure in the pyloric region, the reasonableness of the results observed by Kelling and by Blake and myself is manifest.

These results have been further confirmed by Tuffier[12] and by Delbet.[13] They have received support also in observations by Leggett and Maury,[14] who traced the course of food by means of strings tied to little bags containing lead shot. As the heavy weight must tend to carry the bags to the lowest point, the occasional first exit of the string through the stoma, in Maury's experiments, should not be wholly unexpected. The possibility of the anastomotic opening rather than the pylorus being at times the path of election cannot, however, be gainsaid; recent experiments by F. T. Murphy and myself have confirmed the earlier work with Blake in showing that occasionally food will take the artificial before it will take the natural course. But there is no doubt, from the wide range of evidence above cited, that in experimental animals the natural exit of the food is through the pylorus, and not through the artificial opening, when both ways are offered.

The claim may again be made that the results of these experiments, which were performed on animals, do not apply to conditions in human beings, where the stomach and intestines are larger structures, and permit the establishment of larger openings. In this connection the experience of Berg is of interest. In 1907 he reported the cases of two persons, who had each an accidentally established duodenal fistula, and were losing a large

amount of food through this unnatural orifice.[15] Berg made a gastro-enterostomy in each patient, and in one of them also tied the pylorus. In the latter case chyme ceased to be discharged. In the former case, however, it continued passing out through the duodenal fistula. This operation on a human being exactly corresponds to Kelling's experiments on dogs, and to the studies by Delbet, mentioned above. The conclusion, therefore, may be justly drawn that, if the pylorus is patent, the gastric contents are forced out through the natural passage rather than through the anastomosis.

On the basis of the consideration just presented, Moynihan has concluded that gastro-enterostomy is most efficient only when gross mechanical obstruction exists. Under no circumstances, and in compliance with no persuasion, however insistent, he has declared, is the operation to be done in the absence of demonstrable organic disease.[16]

In animals in which gastro-enterostomy had been performed, and the pylorus had been left unclosed or only partly occluded, Blake and I repeatedly observed a circulation of the food. The food was forced through the pylorus, was pushed thence through the duodenum, and driven into the stomach again through the stoma. We have watched animals a half-hour at a time, and over and over again at short intervals during this period food has entered the duodenum from the pylorus, and gone through the regular course, only to merge once more with the mass in the stomach. Usually at these times no food was seen passing into the intestine beyond the stoma. It was of interest and of practical importance to observe that the food circulated most constantly when the stomach wall was stretched by a large amount of contents. The stretching separates the edges of the opening to which the intestine is attached, and as the edges separate, the intestine is drawn straight between them. Thus it forms a flat cover to the stoma, becoming, in short, practically a part of the gastric wall. In the stretching and flattening of the attached coil of intestine, the entrances into the lumen of the gut are changed to narrow slits. These slits may, indeed, be so much narrowed by pressure applied to them from within the stomach that they act like valves, permitting material to enter, but preventing its escape.

The effectiveness of these " valves " we tested in the excised stomach by tying the pylorus and filling the organ with water.

As the gastric wall became stretched and the internal pressure increased, almost no water escaped through the stoma into the intestine. And when the cardia was closed and the stomach and its fluid contents further pressed by hand, the "valves" were still more effective in preventing leakage (see Fig. 5). Not more than a moderate distension of the stomach after gastro-enterostomy seems, therefore, an essential condition for effective action of the anastomosis.

The circulation of the food above described did not in our experiments result in the symptoms of "vicious circulation." The animals never vomited in consequence of repeated entrance of food from the duodenum into the stomach. Indeed, the observations of Boldireff[17] indicate that the presence of a certain amount of bile and pancreatic juice in the stomach may be quite normal. And Kaiser, after citing numerous observers who found bile almost invariably present after gastro-enterostomy in human beings, has declared that he does not regard its presence there unfavourably.[18]

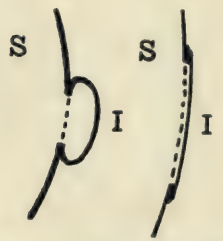

FIG. 5.—DIAGRAM SHOWING HOW STRETCHING THE STOMACH IN GASTRO-ENTEROSTOMY MAY CAUSE THE ATTACHED PART OF INTESTINE TO BECOME ALMOST CONTINUOUS WITH THE GASTRIC WALL, AND THE ENTRANCES INTO THE INTESTINAL LUMEN TO BE CHANGED TO MERE SLITS.

S, stomach; I, intestine.

Retention of food in the stomach, with subsequent repeated vomiting, such as attends the so-called "vicious circulation" after gastro-enterostomy, was associated usually, in our experiments, with obstructive kinks and other demonstrable obstacles to the easy passage of the food. In the case of fatal kinking observed by us the trouble was invariably at the distal point of that part of the intestine which was attached to the stomach. Sharp turns in the intestine are normally straightened without difficulty by the injection of material driven along by peristalsis. When a kink forms immediately beyond the stoma, however, this force is not at hand to straighten it, for peristaltic activity has been abolished in the intestine proximal to the kink by cutting the necessary circular fibres. The contraction of the interrupted circular muscle evidently can have no other effect than that shown in Fig. 5—*i.e.*, a shortening of the intestinal wall between the attachments to the stomach. The only force

tending to obviate the kink is the pressure on the food in the stomach, which in the cardiac portion is slight. The rational procedure, therefore, is to attach a narrow band of the distal gut continuously to the stomach wall for several centimetres beyond the stoma. The gut is thus kept straight throughout a distance which permits peristalsis to become an effective force. From clinical considerations, Kappeler has come to the same conclusion, and has recommended fastening to the stomach wall 4 to 6 centimetres of both the proximal and distal loops, for the purpose of avoiding sharp turns.

If gastro-enterostomy is performed when the pylorus is entirely obliterated, the new opening presents the only outlet from the stomach. Under these circumstances an important mechanism operating normally in the duodenum may become, to some extent, impaired. The effect of acid chyme in causing a flow of pancreatic juice and bile is now well known. Bayliss and Starling[19] found that the action of acid in causing a flow of pancreatic juice and bile is not confined to the duodenum, but is effective in approximately the upper 60 centimetres of the dog's intestine. It is probable, therefore, that secretin is produced at least through the duodenum and jejunum of man. If the anastomosis is made between the stomach and the uppermost part of the small intestine, the mechanism for the flow of these important digestive juices would be retained.

With the pylorus closed and the stoma as the only exit, one might suppose at first that the admixture of the chyme with pancreatic juice and bile would be largely abolished. But that need not necessarily be the case. Probably a certain amount of the pancreatic juice and bile is carried into the jejunum and ileum, and there mixed with the food. Furthermore, in our X-ray observations on experimental animals, the food was repeatedly seen passing from the stoma into the proximal loop. No sooner did it thus pass towards the pylorus than a peristaltic wave was started which swept the food at once into the stoma again. As the circular fibres were not complete at the stoma, the food was not pressed past the opening into the distal gut, but was forced into the stomach. No sooner had the wave gone by than the food was pressed again into the proximal loop. Thereupon a new peristaltic wave once more pushed the food toward the anastomotic opening; back it was pressed again, however, when the wave reached the cut fibres. This process,

repeatedly observed, must at least mix some of the food very thoroughly with the digestive secretions poured into the duodenum. Kelling[20] has recorded a surgical case in which he observed through a fistula a similar passage of some of the food backwards into the duodenum from the stoma. Only a relatively small part of the food, however, can be treated in this manner, and at best this to-and-fro shifting is a poor substitute for the process which normally mixes the juices and the chyme in the first part of the small intestine.

The observations on the effects of gastro-enterostomy above described affect the conclusions drawn from studies of digestion and absorption after this operation. These conclusions are based on figures obtained in some instances with the pylorus patent, in other instances with it occluded. Possibly the wide variations in the amounts of the different foodstuffs, particularly fats, which have been reported as not absorbed after gastro-enterostomy, may be explained by the degree of deviation of the chyme from its normal course because of the differing patency of the pylorus.

From the considerations suggested by our experimental work, Blake and I concluded that the stoma should be large and near the pylorus, that circulation of the food could be rendered less likely by avoiding conditions which stretch the stomach, and that kinks might be obviated by attaching several centimetres of the distal gut to the stomach. The probability of a circulation of the food, however, if the pylorus is left open, the non-mixture of much of the food with the digestive and neutralizing fluids in the duodenum, and the ever-present danger from kinks, despite care, make the operation not an ideal one. When pyloroplasty is possible, these objections can be avoided. And, as Blake and I pointed out, in accordance with our observations, the rapid exit of food from the stomach after cutting the pyloric sphincter is prevented by rhythmic contractions of muscle rings in the duodenum—an activity which replaces in part the functions of the pylorus, and also mixes the food with the pancreatic juice and bile.

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CHAPTER VIII

THE PASSAGE OF DIFFERENT FOODSTUFFS FROM THE STOMACH

In 1901, while studying the movements of the intestines, I observed that not only did salmon begin to leave the stomach later than bread and milk, but that it was slower in reaching the large intestine ; and in the report of the research I called attention to this interesting difference. A careful study of this phenomenon, and, in general, of the manner in which the different foodstuffs are mechanically treated by the alimentary canal, seemed a promising basis for understanding the agencies by which the movements are controlled. Accordingly, experiments were undertaken, directed towards the application of the X rays to the purposes of such an investigation. Since the method devised has proved serviceable in a variety of directions, I shall describe it in some detail.

Among the first essentials for simplicity of method in a study of the mechanical treatment of foods by the stomach and intestines is the employment of foods as purely protein, fat, or carbohydrate, as possible. Such foods were selected. Boiled beef free from fat, boiled haddock, and the white meat of fowl, are examples of the proteins that were fed ; beef suet, mutton and pork fat, are representatives of the fats ; starch paste, boiled rice, and boiled potatoes, of the carbohydrates. A uniform amount—25 c.c.—was invariably given. The food was always finely broken or pressed in a mortar, and, if carbohydrate or protein, was moistened with enough water to produce, as nearly as could be judged by the eye and by manipulation, the uniform consistency of thick mush. Bismuth subnitrate, 5 grammes, thoroughly mixed with each 25 c.c. amount, rendered it opaque to the X rays.

In all cases full-grown cats, deprived of food for twenty-four or thirty hours previous to the experiment, served as subjects

for the observations. The animals were either permitted to eat from a dish, or were placed on holders and fed from a spoon, usually with little or no difficulty, and released as soon as fed. A half-hour and an hour after the feeding, and thereafter at hourly intervals for seven hours, the animals were fixed in the holders, observed, and the conditions recorded. With proper assistance, four or five animals can be examined at one sitting.

The records consisted of outlines of the shadows of gastric and intestinal contents traced on transparent paper laid on the fluorescent screen. If in any case there was doubt that all the shadows had been recorded, an electric light, flashed momentarily on the tracing before its removal from the screen, per-

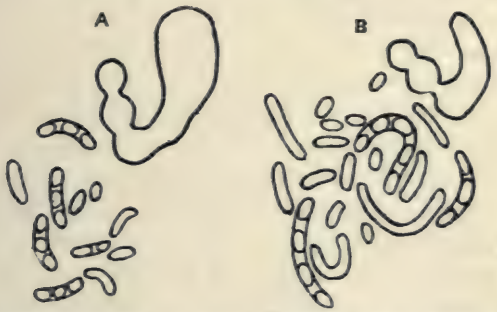

FIG. 6.—TRACINGS OF THE SHADOWS OF THE CONTENTS OF THE STOMACH AND INTESTINES MADE TWO HOURS AFTER FEEDING, IN ONE CASE BOILED LEAN BEEF (A), AND IN THE OTHER BOILED RICE (B).

The small divisions in some of the loops represent rhythmic segmentation.

mitted the outlines drawn on the paper to be compared with the shadows, and the outlines thus verified.

Since the diameter of the intestinal contents varies only slightly (see Fig. 6), the area of cross-section of the contents may be disregarded, and the aggregate length of the shadows taken to indicate the amount of food present. Thus by comparing the aggregate length of these shadows it is possible to judge the relative amounts of a food in the intestine of an animal at different times after feeding, as well as the relative amounts of different foods in a series of animals, or in the same animal in a series of experiments, at any given interval after the food was ingested. For example, in one case, the original record of which is reproduced in Fig. 6, the protein in the intestine two hours after feeding was 20 centimetres (the aggregate length of the

masses); and in another case the amount of carbohydrate, at the same time after feeding, and similarly measured, was 43 centimetres. By this method the observer, without interrupting or interfering with the course of digestion, can know when food first leaves the stomach, the rate at which different foods are discharged into the intestine, the time required for passage through the small intestine, and the mechanical treatment which the food receives. Only during the brief periods of making the records are the animals in any way disturbed; between observations they rest normally and quietly, wholly unrestrained. That the results obtained by the use of the method are not due to individual peculiarities was proved by observing the same animal repeatedly with different foods, and finding the results characteristic of the food, and not peculiar to the animal. Animals once used were not used again within three days.

The method has obvious defects: (1) The loops of intestine are not always parallel with the screen, and the loops not parallel do not always make the same angles with the screen surface; the shadows cast by the contents of the loops must therefore be variously foreshortened. In extenuation of this defect, it may be said that the animals were stretched on their backs, and that the ventral abdominal wall was flattened, both by the stretching and by the pressure of the fluorescent screen laid upon it; the loops therefore must have been nearly parallel with the screen, except at short dorso-ventral turns from one loop to another. That the foreshortening of the shadows in the loops and turns was not a serious source of error was repeatedly proved by tracings made before and after a rearrangement of the loops by abdominal massage; the tracings showed that only slight variations in the aggregate length of the shadows resulted. (2) By overlapping of the loops two masses of food, or parts of two masses, may cast a single shadow. Care was invariably taken to obviate this error by pressing apart with the fingers loops lying close together. (3) May not the bismuth subnitrate and the food separate, and the shadows then be misleading? This separation doubtless occurs to some extent in the stomach. To test the question with reference to the intestinal contents, which are much more important for the reliability of the method, animals were fed the three different kinds of food, and were killed from two to six hours after the feeding. The intestinal mucosa was remarkably free from any perceptible separate

deposits of the heavy powder, and the well-limited masses of material scattered at intervals along the gut were invariably mixtures of bismuth subnitrate and the food. Naturally, as part of the food becomes digested, and as fluids constantly interchange between the intestinal mucosa and the food-remnant in its onward movement, the relation of the bismuth subnitrate to the food must vary; but examination proved that the remnant does not become fluid to a degree which prevents it from being a vehicle for the transmission of the bismuth salt, nor, on the other hand, does the percentage of bismuth fall until it no longer indicates the presence of alimentary material. The changes in the relation of the bismuth salt to the food, from absorption of food or secretion of fluids, are clearly much less in the early stages of intestinal digestion, when little absorption and digestive alteration have occurred, than they are later. The application of the method to the determination of the rate of discharge through the pylorus is therefore justified only in the first two or three hours after digestion, before much absorption has taken place. (4) The subjective differences between observers, the personal equation in making records, is another possible source of error. That Magnus[1] and men working with him, and Hedblom[2] working with me, have employed the method with no essential variations from my original results indicates that the personal equation need not be great. (5) The variations in the thickness of the food-masses at different times, and the variations in the individual rates of absorption of the different foods, are two other possible faults of the method. These defects, however, must be regarded, especially in the early stages of intestinal digestion, as relatively slight, compared with the great and characteristic differences in the amount of food present in the intestine when carbohydrate, fat, and protein foods, are separately fed.[3]

The time during which various foods remain in the stomach has by some perverse chance come to be regarded as an indication of their digestibility. Tables of "digestibility," based on this conception, have long been published. Such a table Beaumont[4] made from observations on Alexis St. Martin, and later Leube,[5] and Penzoldt and his pupils,[6] studied by means of the stomach-tube the duration of gastric digestion of various foods, and tabulated their findings. For several reasons, these figures are not satisfactory for judging the rate at which the stomach is emptied. The observations were made either on a pathological

subject or on persons whose digestive processes had been interrupted by the introduction of a stomach-tube. The results, moreover, express merely the time when the stomach was found empty; they give no hint as to the moment when food first passed the pylorus, or as to the amounts, large or small, which entered the intestine at any stage during digestion. Also, if comparisons are to be made, the amount of food given should be known, for a large amount will evidently remain longer in the stomach than a small amount. Beaumont's records indicate frequent inattention to this factor, and Leube's observations have the same defect. Although Penzoldt and his fellow-workers recorded the amounts, they did not give systematically the same amounts, and the stomach therefore was not always dealing with the same volumetric problem. Furthermore, these investigators did not regard the consistency of the food—a factor of importance, as we shall later learn; nor did they attempt to simplify conditions by the use of fairly pure foodstuffs, for their purpose was to discover how ordinary articles of diet were treated in the stomach.

Since my purpose was to observe how different foodstuffs, other conditions remaining as nearly as possible the same, are treated mechanically by the stomach and intestine, I selected foods predominantly fat, carbohydrate or protein, and fed them in uniform amount and consistency. Differences of treatment then might reasonably be associated with differences in the foodstuffs. We shall first consider the results when fats are fed.

The Discharge of Fats.—In selecting fat food, particular attention had to be paid to the effect of temperature on consistency; a fat, mushy at room temperature, might be much too fluid at body temperature. Care was taken, therefore, to choose fats or fatty tissues which, when mixed with bismuth subnitrate, presented at body temperature about the same degree of viscosity as the carbohydrate and protein preparations.

The rate at which fats leave the stomach may be judged from the curve of the fat-content of the small intestine (Fig. 7, dash line), plotted from the average figures of sixteen cases of fat-feeding.* The curve shows that the emergence of the fat from the stomach begins rather slowly—in eight of the sixteen cases, indeed, nothing left during the first half-hour of digestion—and continues

* The figures which this and other curves express can be found in the original reports of the investigations.

at such a slow rate that there is never any great accumulation of fat in the small intestine. Fats almost invariably are present in the stomach during the seven hours of observation ; in one case an animal was killed six hours after receiving 25 c.c. of mutton fat, and about 11 c.c. had not yet departed. The long, low curve is characteristic. It indicates a slow discharge from the stomach, approximately as slow as the departure of the fat from the small intestine by absorption and by passage into the large intestine.

How do the results of the X-ray method accord with other evidence as to rate of emergence of fat from the stomach ? In 1876, Zawilski,[7] while studying the duration of the fat-stream

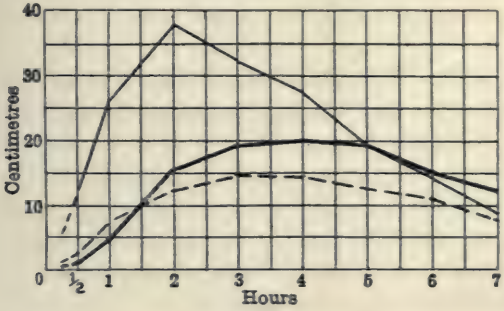

FIG. 7.

These and all other similar curves presented later show the average aggregate length of the food-masses in the small intestine at the designated intervals after feeding. These are the curves for various fat foods (dash line), protein foods (heavy line), and carbohydrate foods (light line)—sixteen cases each.

through the thoracic duct, was impressed by the length of time necessary to complete the absorption of fat. Three animals, fed 150 grammes of fat mixed with other food, were killed after different intervals ; after five hours of digestion, 100 of the 150 grammes were still in the stomach, and even after twenty-one hours 10 grammes were still there. In the small intestine the variation in amount was only slight ; about 10 grammes were found at five hours, and about 6 grammes at twenty-one hours. While investigating the absorption of fatty acids, Frank[8] confirmed the observations of Zawilski : the fat stayed long in the stomach, and a fairly uniform amount was present at various times in the small intestine. And, again, in observations incidental to another investigation, Matthes and Marquadsen[9] con-

firmed the statements of Zawilski and Frank. The testimony of different observers was thus far harmonious. Thereupon Strauss denied that fat remains long in the human stomach.[10] His methods, however, were hardly comparable with those of the previous investigators ; only one-fourth of the food was fat, it was given with much liquid, the observations were few, and on only one patient.

The results obtained by the X-ray method, therefore, agree with, and amplify, the evidence offered by Zawilski, Frank, and Matthes and Marquadsen. The long delay of fat in its passage through the alimentary canal occurs in the stomach. Fat passes from the stomach about as rapidly as the small intestine disposes of it ; as a rule, therefore, the amount of fat in the small intestine is fairly constant in quantity and relatively slight in amount.

The Discharge of Carbohydrates.—The rate at which carbohydrates leave the stomach can be judged from the curve (Fig. 7, light line), particularly during the first two hours of digestion. In my first observations on the movements of the stomach, bread was seen in the duodenum about ten minutes after feeding. The curve representing the content of the small intestine after feeding carbohydrates shows that this early emergence of the starchy food from the stomach is followed by an abundant discharge. In a half-hour the amount of carbohydrate present has almost equalled the maximum for fat, and at the end of an hour that amount has more than doubled. The abrupt high rise of the curve to a maximum at the end of two hours indicates the great rapidity of discharge. And as the stomach was usually almost empty about three hours after feeding the standard amount of carbohydrates, the slow fall in the curve during the last four hours of observation records in the main the gradual departure of the food from the small intestine through the absorbing wall and into the colon.

The testimony of Penzoldt and his pupils,[11] that the delay in discharge of carbohydrates from the human stomach is usually not great, is in harmony with the more detailed observations on experimental animals. That potato leaves the human stomach rapidly, and that the gastric juice cannot attack it to any extent, Marbaix reported[12] in 1898, and he suggested that an important question lies here. The answer to that question we must soon consider. For the present we need only note that all the

evidence for a rapid passage of carbohydrate food through the pylorus is concordant. As a consequence of this rapid exit the small intestine receives a large bulk in a relatively short time.

The Discharge of Proteins.—The heavy line in Fig. 7 is a curve plotted from the average figures for the content of the small intestine after feeding four representative proteins in sixteen cases. The striking feature of the protein curve during the first two hours is its very slow rise. In nine of the sixteen cases no food had left the stomach at the end of the first half-hour, and in eight cases the small intestine had not received at the end of an hour more than 4 centimetres of food.

The main portion of a diet is more likely to be composed of carbohydrates or proteins, or of the two combined, than of fats alone. To digest a diet consisting chiefly or even largely of fat is an unusual task for the digestive apparatus. The mechanical treatment of carbohydrates and proteins is therefore of more importance practically than the treatment of the fats; and the fact that the stomach is more habituated to the presence of carbohydrates and proteins in large amounts makes a consideration of the differences of treatment of these foodstuffs more significant than a comparison involving the fats.

The curves representing the carbohydrate and protein discharge from the stomach are strikingly different. At the end of a half-hour the average figures indicate that eight times as much carbohydrate as protein has left the stomach; at the end of an hour more than five times as much, and even at the end of two hours, when much carbohydrate food has probably been absorbed, considerably more than twice as much carbohydrate as protein is present in the small intestine.

The remarkable difference between the carbohydrate and the protein rapidity of departure from the stomach assumes special significance when the action of gastric juice on these two foodstuffs is considered. That the carbohydrates, which are not digested by the gastric juice, should begin to leave the stomach soon after being swallowed, and should pass out rapidly into a region where they are digested, whereas the proteins, which are digested by the gastric juice, should be retained in the stomach sometimes for a half-hour or more, without being discharged in any considerable amount, indicates the presence of an important digestive mechanism.

With the purpose of securing further evidence of the action of this probable mechanism, various combinations of foodstuffs were fed, and the rate of passage from the stomach studied by the method already described.

The Discharge when Carbohydrate or Protein is Fed First.—As we have learned, when different kinds of foods are fed one after another, the first food swallowed fills the pyloric vestibule and lies along the greater curvature of the stomach, and the later food is pressed into the midst of that part of the earlier food which occupies the cardiac end. Thus, if carbohydrates are fed first and proteins second, the carbohydrates will be in contact with the pylorus and will predominate in the pyloric end of the stomach, while the proteins will be found in larger amounts towards the fundus.

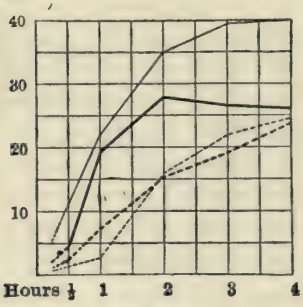

FIG. 8.

The heavy line is the curve after feeding moistened crackers first, lean beef second (four cases); the heavy dot line, after feeding lean beef first, crackers second (four cases). The light line is the curve for crackers alone, the light dot line for lean beef alone (four cases each).

Does the presence of proteins in the cardiac end of the stomach retard the exit of carbohydrates lying near the pylorus? Or if the proteins are near the pylorus, does the presence of the carbohydrates in the cardiac end cause an early exit? To answer these questions, 12·5 c.c. of crackers and water, and 12·5 c.c. of boiled lean beef, each mixed with 2·5 grammes of subnitrate of bismuth, were fed—in one series, crackers, then beef; in another series, beef, then crackers.

The results are represented in Fig. 8. The rate of discharge when carbohydrates were fed first should be compared with the rate when proteins were fed first. When the crackers were near the pylorus, the discharge for two hours was almost as rapid as when crackers alone were given. At the end of two hours, however, the curve ceased to follow the normal for crackers; there was a checking of the outgo from the stomach, which is reasonably explained by assuming that the beef by that time had come to the pylorus in considerable amount, and was as usual passing out slowly. On the other hand, when the beef was first at the pylorus, the curve was in close approximation to the

normal for beef during the first four hours, and after that time, as the crackers came to the pylorus in greater amount, the curve continued to rise, while the curve for beef alone fell. In this combination, never during the first three hours was there half as much food in the small intestine as when crackers alone were fed. The presence of protein near the pylorus distinctly retarded the onward passage of carbohydrate food lying in the cardiac end.

It is noteworthy that when beef was fed first the stomach still contained considerable food even six hours after feeding—three hours longer than the period for carbohydrates alone. On the other hand, when crackers were fed first, most of the food had left the stomach at the end of four hours—only about an hour longer than the carbohydrate period. Since gastric peristalsis persists while food is present in the stomach, this experiment seems to indicate that serving the cereal before the meat at breakfast, and the old custom of eating the pudding before the beef, are rational and physiologically economic arrangements. If the carbohydrate, however, follows the protein, careful chewing, as we have learned, will permit salivary digestion to continue in the cardiac mass during the period of delay.

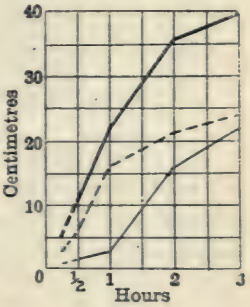

FIG. 9.

The dash line is the curve for equal parts of moistened crackers and boiled lean beef, the heavy line for crackers alone, and the light line for beef alone (four cases each).

The Discharge when Mixtures are Fed.—Inasmuch as what we eat is generally a mixture of the various foodstuffs, it was of interest to discover what effect combinations of the foods, from which characteristic curves had been secured, might have upon those curves. For this purpose, carbohydrates, fats, and proteins, were mixed in pairs, in equal amounts, to make 25 c.c. of food, and this mixture, with 5 grammes bismuth subnitrate, was fed, and the results recorded.

To test the effect of mixing carbohydrate and protein on the rate of gastric discharge, equal parts of lean beef and crackers were given. In Fig. 9 a comparison is presented between the treatment of the mixed foods and the same foods fed separately. Only the changes during the first three hours

are taken for consideration, since they are most significant in judging the rapidity with which the stomach empties. The amount of the mixed food in the small intestine at the end of a half-hour was nearer the carbohydrate than the protein figure, but in general, as the curves show, a mixture of carbohydrate and protein foods in equal parts resulted in a rate of discharge which was intermediate: the mixed food did not leave the stomach so slowly as the proteins, nor so rapidly as the carbohydrates. This conclusion was verified by obtaining similar results when boiled haddock and mashed potato were mixed and fed.

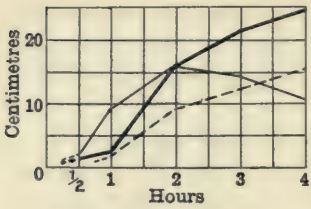

FIG. 10.

The heavy line is the curve for lean beef alone, the light line for beef suet, the dash line for a mixture of beef and suet in equal parts (four cases each).

Boiled lean beef and beef suet mixed in equal amounts served for observations on the effect of combining fat and protein. Comparison of the curve for the mixture with the curves for the two constituents fed separately (Fig. 10) reveals at once that the combination is discharged more slowly than either the lean beef or the suet fed alone. In other words, the presence of fat causes protein to leave the stomach even more slowly than the protein by itself would leave. Feeding haddock and mutton fat in equal parts corroborated the other observations; after two hours the small intestine had only two-thirds as much of the mixed food as of the haddock when fed alone. The long delay in the initial passage of salmon from the stomach (which contrasted so strikingly with the rapid discharge of bread, and suggested the investigation) was probably due to the presence in salmon of more than half as much fat as protein.

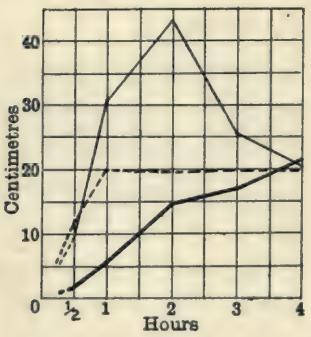

FIG. 11.

The light line is the curve for mashed potato, the heavy line for mutton fat, and the dash line for mixed potato and mutton fat (four cases each).

Mashed potato and mutton fat, and moistened crackers and beef suet, mixed equally in each combination, were used in study-

ing the effect of uniting fats and carbohydrates. In each series of observations the passage of the mixed food from the stomach was more rapid at first than the normal for the carbohydrate used (see Fig. 11). Very soon, however, the fats had a retarding effect on the outgo of the carbohydrate, so that the curve for the mixed foods after the first hour ceased to rise, and never even approximated the height of the carbohydrate curve. We may reasonably conclude, therefore, that the addition of fat in large amount (50 per cent.) to carbohydrate has the same effect, though not to so great a degree, as the addition of fat to protein : the fat retards the exit of either foodstuff from the stomach into the intestine.

The striking differences in the rapidity of discharge of different foods from the stomach, the importance of which I need not emphasize, can all be explained quite simply when we understand the remarkable mechanism of the pyloric sphincter.

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CHAPTER IX

THE ACID CONTROL OF THE PYLORUS

Clinical studies with the stomach-tube,[1] investigations through duodenal fistulas,[2] and, as we have already seen, X-ray observations on the undisturbed subject, combine to prove that the stomach is emptied *progressively* during the course of gastric digestion, and not suddenly at the end, as some investigators have stated.[3] The X-ray studies and the examinations through duodenal openings have further demonstrated that the chyme does not pass through the pylorus at the approach of every peristaltic wave, but emerges *occasionally*, at irregular intervals. The irregular opening of the pyloric passage after periods lasting from ten to eighty seconds I noted in my first report of gastric movements,[4] and these results were in close agreement with the observations of Hirsch and others on dogs with duodenal fistulas, that chyme comes from the stomach at intervals varying between one-fourth of a minute and several minutes.[5]

Both mechanical and chemical agencies have been invoked to explain the emptying of the stomach. These agencies have been supposed by some investigators to act in the stomach, by others to act in the intestine.

That mechanical agencies acting in the stomach control the exit of food has been claimed by those who believe that chyme is discharged only after several hours of gastric digestion. They declare that the pyloric sphincter, although able to withstand the repeated peristaltic pressure in the earlier stages of chymification, is overcome by the more intense constrictions in the later stages.[6] We know, however, that a delay of several hours in the discharge from the stomach is abnormal. The moving constriction rings do indeed press deeper into the gastric contents as digestion proceeds, but this late augmentation of contraction does not explain the normal gradual exit during earlier stages of

chymification, when wave after wave passes, with fairly uniform depth, and yet every now and then some chyme departs. The occasional discharge of chyme from the stomach cannot therefore be attributed to an occasional increase of intensity of the peristaltic constrictions.

The effect of mechanical conditions in the intestine on gastric evacuation was first pointed out in 1897 by v. Mering,[7] who found that the introduction of a large amount of milk into a duodenal fistula checked the exit of water from the stomach. The next year Marbaix[8] published a paper on evacuation of the stomach as affected by a state of repletion of various parts of the intestine. A state of repletion in the upper half of the small intestine induced by injections through fistulas inhibited the discharge from the stomach.* In order to cause the reflex, however, even in the first fourth of the intestine, the injected liquid had to occupy a considerable extent of gut. For example, filling the gut from 10 to 25 centimetres beyond the pylorus caused no inhibition of the discharge. But much less than 15 centimetres of continuous content is normally present in the upper intestinal tract. The tracings of X-ray shadows (see Fig. 6, p. 85) show that the intestinal contents are normally disposed in separate short masses. Under natural conditions, therefore, the extensive uninterrupted surface of contact required by v. Mering's and Marbaix's explanation, in order to prevent a continuous outpouring from the stomach, does not exist. As the continuous outpouring, nevertheless, does not occur, their results do not explain the normal control of gastric discharge. Von Mering's and Marbaix's contribution has been supported, however, by Tobler's observation[9] that the rapid inflation of a balloon in the duodenum checks the passage of food from the stomach. This experiment, like v. Mering's and Marbaix's, does not explain normal conditions, because, as I have shown,[10] chyme normally gathers in the duodenum gradually, by repeated small additions, and even when accumulated lies as a slender strand which does not distend the gut. Each strand thus formed is soon hurried forward some distance along the tube, thus clearing the duodenum for new accumulations.

* An investigation of the motor functions of the stomach after pyloroplasty (see Cannon and Blake, *Ann. Surg.*, 1905, xli., p. 707) has proved that, although the upper part of the small intestine may become filled with food, there is no cessation of peristalsis. The effect noted by v. Mering and Marbaix is therefore probably due to closure of the pylorus.

Though the passage of food from the stomach may be checked by artificially filling a long piece of the upper intestine or by sudden distension of the gut at one point, such conditions cannot account for any natural control of gastric discharge from the intestinal side, because such conditions are not normally found. The evidence, therefore, is opposed to the conception that mechanical agencies, acting either in the stomach or in the intestine, play an important part in controlling the normal gastric evacuation.

We turn now to a consideration of chemical agencies that have been invoked to explain the emptying of the stomach. As long ago as 1885 Ewald and Boas found,[11] by use of the stomach-tube on man, that there was a considerable development of free hydrochloric acid before the gastric contents began to be notably diminished in amount. Where the acid may have had its effect—whether on peristalsis or on the pyloric sphincter—was not determined. Later, Penzoldt,[12] in studying the periods during which various common foods remain in the stomach, noted that foods delaying the appearance of free hydrochloric acid remain longest. Verhaegen,[13] on the other hand, declared that it matters little for the passage through the pylorus whether the food is acid or neutral. Although Penzoldt's careful work was of clinical value, it is inadequate to explain the factors in control of gastric evacuation. The varying composition of the foods he used, the varying amounts and consistencies, and the failure of his method to indicate the rapidity of gastric discharge as digestion proceeds, render difficult the drawing of exact conclusions from Penzoldt's results. In the presence of strong opposing evidence, Verhaegen's contention that neither acidity nor neutrality of the chyme has any effect on the emptying of the stomach may reasonably be doubted. Furthermore, his observations were made with the stomach-tube, on only four individuals, two of whom were pathologic.

The first evidence of the action of chemical agencies in the duodenum on the emptying of the stomach was brought forward by Hirsch. In 1893 he reported[14] that solutions of inorganic acids left the stomach slowly, and he inferred that the slow exit was due to the stimulating effect of the acid on the mucosa of the duodenum. Later, Serdjukow, one of Pawlow's students, inhibited gastric evacuation by introducing acid into the duo-

denum through a fistula,[15] thus confirming the conclusion of Hirsch. Tobler's results[16] also substantiate it.

The main defect of the above methods as means for determining the nature of the chemical control of gastric discharge is their failure to distinguish between the two factors concerned in emptying the stomach: one, the pressure to which the food at the pylorus is subjected by recurring peristaltic waves; the other, the action of the pyloric sphincter. Not until the X-ray method was used was it possible to watch, under normal conditions, both gastric peristalsis and the exit of food through the pylorus. Until the application of the X-ray method, therefore, a clear distinction between the normal effects of these two factors could not be made.

Evidently the normal exit of food might be occasional because of occasional peristaltic constrictions, or occasional specially strong peristaltic constrictions, pressing the gastric contents against an easily opened pylorus; or, on the other hand, the occasional passage might be due to an occasional relaxation of the pylorus in the presence of fairly uniform conditions of pressure.

Some of the investigators whose work has already been mentioned have, indeed, ascribed the control of gastric discharge solely to the action of the pyloric sphincter. Marbaix, for example, writes of the influence of the repletion of the intestine on the closure of the pylorus.[17] His evidence for this limitation is not clear. Von Mering, on the other hand, recognized that intestinal repletion might check gastric discharge by stopping peristalsis, and he resected the pylorus in order to differentiate, if possible, between the peristaltic and the pyloric factors.* The failure to make this differentiation is the essential flaw, for the present analysis, in the methods of Ewald and Boas, Penzoldt, Hirsch, Serdjukow, and Tobler. Their results, therefore, while significant, cannot serve for a conclusive determination of the control of gastric evacuation.

The evidence that under normal conditions peristaltic waves are continuously running over the stomach, so long as food

* The possible confusion of the two factors is illustrated in Pawlow's report of Serdjukow's experiments. He states (*The Work of the Digestive Glands*, London, 1902, p. 165) that acid chyme entering the duodenum reflexly occludes the pyloric orifice, "and at the same time reflexly inhibits the propulsive movements of the organ (stomach)." Clearly the occlusion of the pyloric orifice alone would account for Serdjukow's results. What is the evidence that peristalsis also was affected?

remains, has been presented in a previous chapter. In my experience, neither ejaculation of acid chyme nor stretching of the duodenum with food pressed through the cut pylorus (see footnote, p. 97) has any tendency to interrupt the sequence of waves. As remarked in the discussion of mechanical agencies acting in the stomach, the waves do not show from moment to moment marked variation of intensity. One of the two factors concerned in gastric discharge—the pressure in the vestibule—is therefore recurrently constant. The control of the discharge, consequently, must reside with the other factor—*i.e.*, with the action of the pyloric sphincter. If the sphincter holds tight, the recurring waves churn the food in the vestibule ; if the sphincter relaxes, these waves press the food out into the duodenum. The pylorus is the " keeper of the gate."

The discharge from the stomach, as we now know, is occasional. The foregoing analysis proves that this occasional discharge must be due to occasional relaxations of the pyloric sphincter. To explain the action of the pylorus, therefore, it is necessary to consider agencies which maintain an intermittent closure—which usually keep the passage shut, yet open it at intervals to allow portions of the chyme to depart. None of the researches on the control of gastric evacuation, discussed in the preceding pages, were definitely concerned with this intermittent closure. Further investigation was desirable to explain the repeated opening and shutting of the pyloric orifice.

Further investigation was necessary also to explain the striking differences in the rate of discharge of different foodstuffs. The facts presented in the foregoing chapter immediately raised the question, What is the pyloric mechanism whereby carbohydrates, not digested by the gastric juice, are permitted to pass quickly into the small intestine to be digested, whereas proteins, digested in the stomach, are there retained to undergo digestion ?

As we have learned, investigators have hitherto regarded factors in the stomach, or factors in the intestine, as controlling gastric evacuation. An interaction of agencies in the two situations has not been considered. A theory based on evidence of opposed effects from a single stimulus acting first in the stomach and later in the duodenum I propounded[18] in 1904, to explain the differential discharge of the different foodstuffs.

The first statement in the theory is that acid coming to the pylorus causes a relaxation of the sphincter. Thus would be

explained why the initial discharge is longer delayed when proteins are fed than when carbohydrates are fed. Both carbohydrate and protein stimulate gastric secretion in abundance, as researches on dogs by Pawlow and his co-workers,[19] and as clinical studies on men, have shown. Inasmuch as carbohydrates do not unite chemically with the acid, free acid is at once present in the stomach; carbohydrates would therefore begin almost immediately to pass through the pylorus. Proteins, on the other hand, join with the acid, and thus retard for some time the development of an acid reaction;[20] the protein discharge would therefore be retarded.

But acid on the stomach side of the pylorus is not the only determinant of pyloric action. The observations of Hirsch and Serdjukow now have their bearing. Since it has been shown that acid in the duodenum does not stop gastric peristalsis, the acid reflex from the duodenum must affect the pyloric sphincter. The second statement in the theory naturally follows—acid in the duodenum closes the pylorus.

It is probable that the pyloric sphincter has normally a greater or less degree of tonic contraction, with occasional relaxations.[21] Certainly it has a tonic contraction persistently strong for some time after food enters the stomach. When protein, for example, is fed, peristaltic constrictions may press the food against the pylorus repeatedly for a half-hour or more (approximately, 150 waves) without forcing food through the orifice.

The whole theory of the acid control of the pylorus may now be stated. The pylorus is tonically closed when food is ingested, and remains closed against recurring pressure. The appearance of acid at the pylorus causes the sphincter to relax. The pressing peristaltic waves now force some of the acid chyme into the duodenum. The acid in the duodenum at once tightens the sphincter against further exit. The same acid also stimulates the flow of alkaline pancreatic juice.[22] Since no inorganic acid is normally present beyond the first centimetres of the small intestine,[23] and since the acid reaction of the contents in this uppermost region is replaced throughout the rest of the small intestine by practically a neutral reaction,[24] the acid chyme must be neutralized soon after its emergence from the stomach. As neutralization proceeds, the stimulus closing the pylorus is weakened; now the acid in the stomach is able again to relax the sphincter. Again the acid food goes forth, and immediately

closes the passage behind until the duodenal processes have undergone their slower change. And thus, repeatedly, until the stomach is empty.* What is the evidence for this theory ?

As the acid of the gastric juice, according to the theory, may have two opposing effects on the pylorus, we shall review first the evidence that acid in the vestibule causes the pylorus to open, and afterwards the evidence that acid in the duodenum causes the pylorus to be kept closed.

The evidence that acid in the vestibule opens the pylorus we shall consider under several headings, as follows :

1. Delaying the appearance of hydrochloric acid delays the initial discharge. In terms of the above theory the quick exit of carbohydrates is due to the early appearance of acid in the stomach. The appearance of acid can be delayed if the carbohydrates are first moistened with sodium bicarbonate. Then the acid would first be neutralized by the alkaline food near the secreting surface and in the churning vestibule ; and only after some time would an acid reaction appear in considerable amount. If the theory is correct, this postponement of the appearance of acid should delay beyond the normal time the initial discharge of the food.

Crackers, rice, and mashed potatoes were chosen as representative carbohydrate foods. The rice was steamed and dried, and the mashed potato was also dried before being used. In all cases 1 per cent. sodium bicarbonate was added to the dried food until a mush was made, of the same consistency as in the standard cases. The carbohydrates thus prepared were mixed with subnitrate of bismuth, and fed, as in the standard cases, in 25 c.c. amounts. The average figures for twelve cases in which the three carbohydrates wet with water were fed, and the twelve cases in which they were fed wet with sodium bicarbonate, are represented graphically in Fig. 12.

The curves show that at the end of a half-hour there had emerged only about one-tenth as much of the food wet with the alkaline solution as of the same food wet with water (in six of the twelve cases no alkaline food had left the stomach) ; at the end of an hour, from a third to a half as much ; and in two hours, from about a half to five-sixths as much. In other words,

* Cohnheim, in his summary of the factors controlling the discharge of food from the stomach (Nagel's *Handb. d. Physiol. d. Mensch.*, Braunschweig, 1907, ii., p. 564), mentioned the theory here propounded, but stated that my evidence for it was not convincing. It is fair to note that at that time the evidence in a complete and detailed form had not been presented.

there has been a marked retardation in the discharge of carbohydrates wet with the alkaline solution. This result is in harmony with the observation by Jaworski on man, that alkalinity of the contents delays the emptying of the stomach.[25]

Sodium bicarbonate delays the appearance of acid in two ways: it checks the secretion of the gastric juice,[26] and for a time it unites with the acid of the gastric juice as rapidly as it is poured out. The evidence here presented shows that experimental conditions delaying the appearance of hydrochloric acid delay the discharge from the stomach.

2. Hastening the appearance of an acid reaction hastens the initial discharge. According to the theory, as already stated, the slow passage of proteins from the stomach is due to their union with the acid of the gastric juice, which prevents the rapid development of a marked acid state.

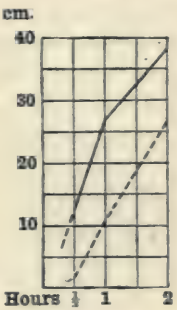

FIG. 12.

The continuous line is the curve after feeding potato, rice, and crackers (four cases each) moistened with water, and the dot-line the same, moistened with 1 per cent. $NaHCO_3$.

Evidence as to this supposition may be secured by feeding protein food that has previously been changed to acid protein. Fibrin, lean beef, and fowl, freed from fat, were chosen as representative protein foods. They were mixed with 10 per cent. hydrochloric acid, and allowed to stand until changed to acid protein. The free acid was dialyzed away until test showed none present. As the change to acid protein was accompanied by swelling of the original substance, the standard protein content was to some extent preserved by feeding the acid protein in twice the usual amount. Doubling the amount of the natural protein notably retards the outgo from the stomach.[27] If changing the natural to acid protein has no effect on the outgo from the stomach, doubling the amount should likewise retard the outgo—certainly should not accelerate it.

Fibrin, fowl, and lean beef were fed as acid proteins in 50 c.c. amounts, and with the same consistency as in the standard cases. In Fig. 13 are presented the curves for the average figures of the twelve cases in which these same foods were given as acid proteins.

The curves show that at the end of a half-hour the stomach had discharged from five to ten times as much acid protein as natural protein; three to ten times as much at the end of an hour; and in two hours about twice as much acid protein as natural protein. Evidently the change to acid protein and the feeding in increased amount resulted not in slowing, but in remarkably accelerating the exit from the stomach. According to Moritz, Tobler, and Lang, protein discharged through the pylorus may be merely acid protein, unaccompanied by free hydrochloric acid.[28] In that case the protein given in these cases is ready to leave the stomach. If any acid is secreted upon it, free acid is at once present, and appears, therefore, earlier than when natural protein is fed. The evidence here given indicates that, when experimental conditions hasten the appearance of an acid reaction, the discharge from the stomach is correspondingly hastened.

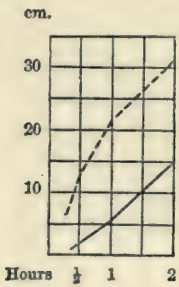

FIG. 13.

The continuous line is the curve after feeding fibrin, fowl, and lean beef (four cases each) as natural protein, and the dot-line the same, as acid protein.

3. The appearance of acid near the pylorus closely precedes the initial discharge. Although in the experimental conditions already described the emergence of food from the stomach occurred as if acid were present to open the pylorus, its presence has only been inferred; there has been no demonstration that acid was present when the first food passed into the duodenum. The relation between the first development of acid and the first exit of the food should be more exactly determined. This can be done by establishing in the vestibule, close to the pylorus, a fistula.

A fistula holding a simple flanged cannula with a removable plug was established in the vestibule in several cats. The cats recovered readily from the operation, and were usually in very good health. In order that the food could be seen with the X rays when it first entered the duodenum, it was always mixed with bismuth subnitrate. When potato was fed, 20 drops of dimethylamidoazobenzol were added—an amount staining the potato orange, and showing a clearly marked change to pink when hydrochloric acid developed. As soon as the potato was given (usually by stomach-tube), the plug was removed from

the cylinder of the cannula, and replaced by a tight-fitting glass syringe. By pulling up the piston the thin mushy contents of the vestibule were drawn slightly into the glass tube. Then any change of colour could be noted. If the original orange colour still persisted, the piston was pushed down again, and thus the food was restored normally to the stomach. Usually such observations were made every four minutes ; during the intervals X-ray observations showed whether food had yet been passed into the duodenum. When lean beef was fed, the colour-change could not be clearly seen, and it was necessary to remove through the cannula a sample of the vestibular contents in a small pipette. The contents were tested for acid with Congo-red, dimethylamidoazobenzol, and tropäolin oo.

Observations through the fistula proved that a delay in the appearance of acid in the contents of the vestibule is associated with a similar delay in the passage of food from the stomach ; that this may occur in spite of vigorous gastric peristalsis ; that under these circumstances the introduction of a small amount of acid near the pylorus causes immediately the exit of food through the pylorus ; and that, whether potato or beef is fed, and whether in the same animal the discharge begins at the usual time or is much retarded, the first delivery of food into the duodenum is normally preceded by the development of an acid reaction in the vestibule.

These observations on the vestibular contents are well supported by studies of the reaction of the discharged chyme. Tobler, London and Sulima, and London and Polowzowa, have tested the chyme collected from a duodenal fistula close to the pylorus. Tobler fed lean beef to his dogs. The repeatedly discharged gastric contents were acid from the beginning, and continued during digestion to be "stark sauer."[29] London and Sulima[30] recorded that when cooked egg-albumin was fed, the discharge from the pylorus was initiated by the pouring forth of an acid fluid. The same condition was recorded by London and Polowzowa[31] after feeding white bread.

4. Hydrochloric acid opens the pylorus of the excised stomach. Magnus has shown[32] that pieces of the small intestine, removed from the body and placed in warm, oxygenated Ringer's solution, will remain alive and, so long as the myenteric plexus is intact, will manifest the typical activities. I have given evidence that the mechanism in control of the differential dis-

charge through the pylorus is independent of the central nervous system.[33] To test whether the mechanism resides in the local nerve plexus, the following experiment was performed :

A cat which had fasted for twenty-four hours was quickly killed by etherization. The empty stomach was removed and placed in oxygenated Ringer's solution (38° C). A glass tube, with a short rubber tube and a water manometer attached, was tied into the cardiac orifice. A small amount of 0·4 per cent. HCl, made blue by the changed Congo red, was introduced through the tube into the fundus, which was held lower than the vestibule. The stomach was now inflated until air bubbled through the pylorus. The rubber tube was next tightly clamped. When the air had ceased escaping—*i.e.*, when pyloric tonus withstood intragastric pressure—the stomach was gently and slowly turned until the acid came to the pylorus. In a moment the blue fluid poured forth into the Ringer's solution. The pylorus had opened.

It might be supposed that the acid coming into the vestibule caused an increased tonus of the gastric musculature, and that thus the pyloric orifice was forced open. The manometer, however, did not show any increase of intragastric pressure. Furthermore, the stomach can be tipped so that the acid fluid enters the vestibule, but does not come to the pylorus. This did not lead to the driving out of more air ; the acid did not notably stimulate contraction of the gastric wall. The opening of the pylorus, therefore, was due to the presence of the acid.

A 1 per cent. sodium bicarbonate solution, coloured red, similarly brought to the pylorus, did not begin to emerge for a considerably longer time, and then usually drifted out into the Ringer's solution as if slowly diffusing. The conclusion is justified that in the living excised stomach acid coming to the pylorus causes the pylorus to open.

We may sum up, therefore, as follows, the evidence that acid on the stomach side of the pylorus signals the relaxation of the sphincter. Moistening carbohydrates with $NaHCO_3$ retards their normally rapid exit from the stomach ; feeding proteins as acid proteins remarkably hastens their normally slow exit ; observations through a fistula in the vestibule show that an acid reaction closely precedes the initial passage of food through the pylorus, that the introduction of acid causes pyloric opening, and that delaying the acid reaction causes retention of the food in the stomach, in spite of strong peristalsis ; and, when the stomach

is excised and kept alive in oxygenated Ringer's solution, the pylorus is opened by acid on the gastric side. What, now, is the proof that acid in the duodenum keeps the pylorus closed ?

The support for the second half of the theory, that acid in the duodenum keeps the pylorus closed, has already been in part suggested. As other observations to the same effect are to be described, however, a brief restatement of the experiments previously mentioned will not be out of place, and will serve to bring all the evidence together.

1. Acid in the duodenum inhibits gastric discharge. In 1893, Hirsch, as already noted, found that inorganic acids left the stomach slowly. When he isolated the stomach, however, the acids departed as rapidly as any other fluid. He explained this difference by assuming that the stomach is controlled by acid reflexes from the duodenum. Serdjukow modified Hirsch's experiment by introducing through a duodenal fistula small quantities of acid solutions or pure gastric juice. By repeated injections it was possible to prevent discharge from the stomach for an unlimited time. Tobler's observations were closer to the normal conditions. He allowed a dog with duodenal fistula to eat 100 grammes of lean beef. The chyme as it emerged was caused to leave the duodenum through the artificial opening. The stomach was thus emptied in about two hours and fifteen to thirty minutes. The next day the dog was given the same amount of the same kind of food, but whenever a portion of the chyme came through the fistula from the stomach, a similar portion of the chyme of the day before was injected through the fistula towards the intestines. The result was that the chyme left the stomach at considerably longer intervals, and was more thoroughly digested. The time of digestion thus became lengthened to three hours and three hours and a half. Tobler's observations have been completely confirmed by Lang.[34]

The experiments of Hirsch, Serdjukow, Tobler, and Lang prove definitely that acid chyme in the duodenum checks the outgo from the stomach. Since we now know that gastric peristalsis is not stopped by the discharge of acid chyme, the effect must be due to the action on the pyloric sphincter. Acid in the duodenum causes pyloric contraction.

2. Absence of the normal alkaline secretions from the duodenum retards gastric discharge. Pawlow has recorded that the passage of acid solutions out of the stomach is remarkably

slower in dogs with a pancreatic fistula than in those without one.[35] In order to test whether the discharge of normal gastric contents is likewise retarded by a similar condition in the duodenum, the following experiment was performed: The larger pancreatic duct and also the bile-duct were tied so as to prevent the flow of the secretions into the intestine. Six and twelve days after the operation the animals were given the standard amount of mashed potato and bismuth subnitrate with the usual consistency. The outgo from the stomach was determined, as before, by measuring the length of the food-masses in the small intestine. Fig. 14 presents a comparison of the discharge under normal conditions and after tying the ducts. Obviously there has been a very marked checking of the normal rapid outgo of the potato from the stomach; nothing out in a half-hour, a fourth the normal amount in an hour, and a third the normal at the end of two hours.

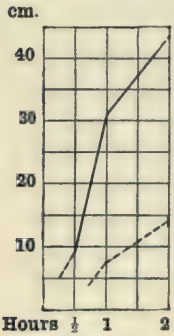

Fig. 14.

The continuous line is the curve after feeding potato (four cases) in normal conditions, and the dot-line the same, with pancreatic and bile ducts tied.

Why there should be no exit of the food during the first half-hour is not clear, but the very slow increase of the intestinal contents thereafter—from 7·5 to 14·5 centimetres in the second hour of digestion, compared with the increase from 10 to 31·5 centimetres in the second half-hour in the normal state—is in harmony with the observation that acid in the duodenum closes the pylorus.

Under normal conditions, acid in the duodenum stimulates the secretion of pancreatic juice and bile. These alkaline fluids must neutralize the acid chyme, for an acid reaction is not found beyond the first few centimetres of the small intestine (see p. 101). The neutralizing of the acid removes the stimulus keeping the pylorus closed. If the alkaline fluids are prevented from entering the intestine, the acid is necessarily neutralized more slowly, the pylorus is kept closed during longer periods, and the emptying of the stomach therefore occurs at a slower rate.

3. Destroying continuity between stomach and duodenum hastens gastric discharge. Additional evidence as to the relations between the duodenum and the pylorus in the control of

gastric evacuation can be secured by setting aside the duodenum, and causing the stomach to empty into a lower part of the gut. The intestine was cut through about 1·5 centimetres beyond the pyloric furrow, and again about 30 centimetres beyond. The upper end of this separated portion was turned in and closed with stitches; the lower end was joined to the gut near the ileocolic opening by an end-to-side junction. The upper end of the main part of the intestine was now united to the small remnant of duodenum contiguous to the pylorus. Thus the stomach emptied, not into the duodenum, but into a piece of the intestine, formerly 30 centimetres beyond.

After recovering from the operation, the animals were fed shredded lean beef of standard amount and consistency. Reference to Fig. 15 shows at once the difference between the factor which acts inside the stomach and the factor which acts in the duodenum to control the pylorus. In the normal, and in the experimental conditions as well, there occurred the retardation of the initial discharge characteristic of proteins. Setting aside the duodenum evidently did not change that. That retardation, according to the conclusions already stated, is an affair of the stomach alone. And the results graphically reported in Fig. 15 serve to confirm those conclusions.

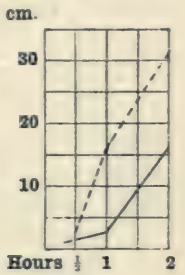

FIG. 15.

The continuous line is the curve after feeding lean beef (four cases) in normal conditions, and the dot-line the same, with the duodenum set aside.

When the food begins to emerge, the figures are suddenly quite different. Instead of 3 centimetres at the end of an hour, 16 centimetres; and twice the normal amount at the end of two hours—such is the effect of destroying the continuity between stomach and duodenum. After the first delay (in one case no food left the stomach for an hour), protein is poured forth at a remarkably rapid rate.

In considering agencies affecting the cardia, we learned that acid in the stomach increased the tonic contraction of the sphincter through a local mechanism. The investigations of Magnus have shown that intestinal reflexes occur in the myenteric plexus. It seemed probable that merely cutting a ring around the intestine as close as possible to the pylorus, and

deep enough to sever both muscular coats, would yield information as to the path of influence from duodenum to stomach. A ring was cut as above described, and the separated edges of the muscular coats were then held together by only the mucosa and the submucous connective tissue. When protein was fed there was again the initial delay—nothing out at the end of a half-hour—and this was followed by an exit almost as rapid as when the duodenum was set aside. We may conclude that the influence from duodenum to pylorus runs through a local reflex, mediated by the myenteric plexus. In the intestinal wall is a local reflex, such that a stimulus causes a contraction above the stimulated point and a relaxation below.[36] The action of acid on the two sides of the pylorus is in exact agreement with this so-called "law of the intestine"; the acid when above causes a relaxation of the sphincter which is below, and the acid when below causes a contraction of the sphincter which is above. As we have already seen, the cardia also obeys this law.

We may sum up, as follows, the evidence that acid in the duodenum keeps the pylorus closed. Acid in the duodenum inhibits gastric discharge, as proved by the observations of Hirsch, Serdjukow, and Tobler—an effect, as we now know, not due to stoppage of peristalsis, but to closure of the pylorus; the stomach empties more slowly than normally when the tying of pancreatic and bile ducts prevents alkaline fluids from neutralizing the acid chyme in the duodenum; the discharge of protein becomes rapid if the pylorus is sutured to the intestine below the duodenum, or if a ring is cut through the muscular coats immediately beyond the pylorus. The effect from the duodenum is thus a local reflex, mediated, like the local reflex of the small intestine, by the myenteric plexus.

When all the factors concerned in the proper functioning of the pyloric sphincter are considered, the simple control of its activity by the action of acid above and below must be regarded as one of the most remarkable automatisms in the body. The highly important part which the pylorus plays seems to have been surmised by the ancients who gave it the name, "keeper of the gate," and called it also "rector" and "janitor justus." How it makes the relations between gastric and intestinal digestive processes orderly and progressive, we shall next consider.

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CHAPTER X

THE CORRELATING FUNCTIONS OF THE PYLORUS, AND SOME CONDITIONS AFFECTING IT

THE great importance of the pylorus in correlating the digestive processes of the stomach and small intestine is perhaps brought out most impressively if we consider what would happen if the sphincter did not perform its proper functions. Let us suppose that it opened as soon as gastric peristalsis started.

We know from Edkins's experiments that gastric juice continues to be secreted because acid, peptone, or sugar solutions affect the mucosa of the vestibule. Evidently, if the pylorus opened as soon as the peristaltic waves started, they would act merely to propel the gastric contents rapidly through the stomach. The food, therefore, would not have time to receive much of the acid secretion of the cardiac end, nor would even the small amount of acid that the food might carry be churned against the mucosa of the vestibule. That the processes in the stomach may advance in an orderly manner, therefore, the gastric contents must be retained until the portion in the vestibule is churned to an acid chyme.

Again, if the food were allowed to depart before becoming acid,* it could not stimulate chemically the duodenal reflex. The pylorus, consequently, would not be held closed, and the upper small intestine would be crowded full of food through an uncontrolled pyloric sphincter. Furthermore, the chyme, unless held back until acid, would not, on entering the duodenum, excite the flow of pancreatic juice and bile. Thus, if the pylorus relaxed at the approach of the first peristaltic wave (after meat had been fed, for example), the food would not only emerge wholly undigested by gastric juice, but would bear no provision for being digested by the pancreatic juice. In order that the

* The somewhat variant case of the fats will be considered later.

pancreatic juice may be caused to flow, and may have time to become mixed thoroughly with the chyme, without being overwhelmed by fresh discharges from the stomach, food must be retained in the vestibule until acid in reaction.

If we grant that the vestibular contents must be acid before being permitted to pass the pylorus, note how favourably the stomach is arranged for the utilization of its secretions. We have already learned that in order to open the sphincter the acid must be at the pylorus. Clearly, if the vestibule secreted acid, the acid would at once open the pylorus and let out the food (meat, for example) before the gastric juice had had opportunity to digest it. But the vestibule does not itself secrete acid. The acid and the food with an acid reaction must be brought from the cardiac end of the stomach and thoroughly mixed with the contents of the vestibule before the pylorus relaxes. The necessity of importing the acid into the vestibule insures a thorough mixing of the food with the gastric juice before the food departs, and provides time for gastric digestion.

We can now appreciate how wonderful an arrangement the acid control of the pylorus is—an arrangement whereby the food is held in the stomach until provision is made for the continuance of gastric secretion, until the gastric juice has had time to act, and until the food can bear with it the acid needed for processes in the duodenum. In the duodenum the acid chyme stimulates the flow of pancreatic juice and bile, and holds the pylorus closed until this chyme has been thoroughly mixed with these digestive fluids. This thorough mixing stops gastric digestion, injurious to the action of the pancreatic ferments, by neutralizing the acid. As the acid is neutralized, the stimulus holding the pylorus closed is weakened, and then the acid in the stomach is again effective in causing the pylorus to open.

We shall find still more reason for admiration of the pyloric reflex when we see how exactly its acid control can be applied in explaining the differential discharge of different foodstuffs. The delay in the initial discharge of protein food we have already explained as due to the union of the first acid secreted with the protein. The continued slow exit can also be explained. The mixing occurs only in the pyloric end ; as we know, the centre of the mass in the cardiac end long remains unchanged in reaction. Since the vestibule does not secrete acid, all the acidity of its contents is due to acid pressed in from the cardiac end. But

unchanged protein, stored in the cardiac end, is also continuously being pressed into the vestibule. There is thus continuous utilization of the imported acid. Since it is altogether probable that a certain degree of acidity is necessary for opening the pylorus, the fresh protein masses, by uniting with the acid and thus reducing the acid reaction, would naturally diminish the rate of exit from the stomach. That this factor is important in checking the rapid outgo of protein food is indicated by the quick discharge of acid proteins, which do not demand large amounts of acid (*cf.* two curves in Fig. 15). Possibly also the protein discharge continues to be slow because protein chyme presents a greater amount of acid for neutralization than does carbohydrate chyme. Tobler and Lang have shown that acid protein in the duodenum will check gastric evacuation.[1] Khigine's results prove that, when 200 grammes of flesh are fed to a dog, 50 per cent. more gastric juice is secreted during the first four hours of digestion than is secreted in the same time when the same amount of bread is fed.[2] The neutralizing of the larger amount of acid in the duodenum would naturally require a longer time, and would result in a slower rate of discharge than would be expected when bread is fed.

In examining the effects of feeding combinations of foodstuffs, we noted that when carbohydrate was fed first, and protein second, the departure of the carbohydrate was not materially checked ; but that when protein was fed first, and carbohydrate second, the protein held back the carbohydrate. In the former case the carbohydrate content of the vestibule did not retard the development there of an acid reaction ; in the latter case the protein did retard that development. This observation indicates that the acid which opens the pylorus acts close to the pylorus—a conclusion which is sustained by the effect of acid in the excised stomach.

When carbohydrates and proteins were mixed in equal parts, the discharge was intermediate in rapidity. This result is in accord with other evidence, for a large proportion of protein was present to unite with the acid secreted, and this would tend to retard the discharge in the usual manner.

In a mixture of fats and proteins in equal parts, the presence of fat caused the mixture to leave the stomach even more slowly than the protein alone. This result also is in accord with the supposition that acid opens the pylorus, for fat alone inhibits,

and fat mixed with protein notably retards and diminishes, the flow of gastric juice.[3] Moreover, the development of an acid reaction is checked by the union of acid with protein. Quite naturally, therefore, this combination of foodstuffs was slowest of all to pass from the stomach.*

Fats mixed with carbohydrates in equal amounts caused the carbohydrates to pass the pylorus at a rate slower than their normal. In this case the fats again retarded and diminished secretion; but the carbohydrates, unlike the proteins, did not further hinder the appearance of an acid reaction. The checking of the outgo can therefore be explained by the effect of the fats in diminishing gastric secretion.

The evidence just presented indicates that typical variations in the rate of discharge of proteins, carbohydrates, and fats, and combinations of these foodstuffs, can be readily explained by the action of acid upon the pylorus. This ability to explain the peculiar differences in the gastric discharge of the different foodstuffs brings additional strength to the evidence already given that acid acting oppositely above and below controls the pyloric passage.

The discharge of fats is peculiar, and requires special consideration. In attempting to understand their prolonged slow discharge, we must first consider their effects both in the stomach and in the duodenum. We know that fat in the stomach does not stimulate the flow of gastric juice. On the other hand, according to Lintwarew,[4] fat in the duodenum, like acid, may check the gastric discharge.

Associated with the absence of gastric secretion there is apparently a low degree of pyloric tonus. Boldireff, for example, has reported that, when fats are fed in considerable amount, a mixture of pancreatic juice, bile, and intestinal secretion, flows back into the stomach.[5] This result could not occur unless at times the pyloric sphincter were in a relaxed state, and unless at

* An important food consisting of a combination of fat and protein is milk. Before being coagulated, milk issues from the stomach in gushes, like water, as we shall see later. Clearly, were not milk quickly coagulated, it would go at once into the intestine, unchanged and not provided with acid to help rouse pancreatic secretion. Once coagulated, however, milk leaves the stomach slowly (Moritz, *Ztschr. f. Biol.*, 1901, xlii., p. 575). According to Tobler (*Verh. d. Gesellsch. f. Kinderheilk.*, 1906, p. 147), the chyme from milk is a clear yellowish fluid, with the protein mostly changed to peptone. Coagulation may be interpreted, therefore, as a conservative provision delaying the passage from the stomach until peptonization has occurred. The slow discharge of a fat-rich milk, after the first few gushes through the pylorus, can be explained by the combination of fat and protein in its composition.

times the pressure in the stomach were less than that in the duodenum. In this connection it is of interest to recall that, of the three foodstuffs, fats produce the slowest rate of gastric peristalsis (see p. 55), and commonly the weakest (*i.e.*, the shallowest) waves. My observations do not support Cohnheim's suggestion[6] that fat in the duodenum stops gastric peristalsis.

Fats differ from carbohydrates and proteins in very seldom constituting the chief elements of a diet. They differ also in not arousing gastric secretion. They are further peculiar in acting by themselves in the duodenum, not only to inhibit gastric evacuation, but also to stimulate the flow of pancreatic juice.[7] Clearly, fats do not require the secretion of gastric juice for changes in the stomach, or for the control of their exit into the intestine, or for the stimulation of a pancreatic secretion specially favourable to their digestion.

Although fats have a special relation to the pyloric mechanism, the alternative possibility of an acid control, even when fats alone are fed, should not be overlooked. Fatty acid may be set free in considerable amount in the stomach by gastric lipase if the fat is fed as an emulsion.[8] A separation of fatty acid also occurs when, in the early stages of fat digestion, pancreatic juice enters the stomach.[9] If, at first, fats readily pass through an easily opened pylorus, the later development of acid in fats in the stomach might cause them to control their own discharge, like other foods which develop an acid reaction of the gastric contents. And in the duodenum it is noteworthy that fats are changed with an effect quite unlike that of the other foodstuffs. Fats cause the pancreatic juice to flow, but the pancreatic juice, instead of diminishing the acidity of the duodenal contents, increases the acidity by separating a still greater amount of fatty acid.[10] Even when dissolved in bile, the fatty acids give the solution an acid reaction.[11] To this increasing acidity of the contents of the upper intestine, as well as to the action of fats themselves, and the weak and sluggish gastric peristalsis which they evoke, may reasonably be attributed the fact that fats pass from the stomach only as fast as they are absorbed or carried into the large intestine.

The low pyloric tonus and the inhibition of gastric secretion —conditions which attend the ingestion of fat—are possibly related through the action of the vagus nerves. Pawlow has shown that the psychic secretion of gastric juice is due to im-

pulses coming to the stomach by way of the vagi.[12] Vagus stimulation also produces an augmentation of the contraction of the pyloric sphincter.[13] Vagus impulses, therefore, cause the initial flow of gastric juice—the psychic secretion—and they also cause increased pyloric tonus. In the absence of one effect of vagus stimulation, we might find the other effect also lacking. Certainly that seems to be true for the fats. It is also a possible explanation of several other conditions of anomalous discharge from the stomach—among them, the discharge of water and egg-white.

Water begins to enter the intestine almost as soon as it enters the stomach ; it may pass out in single gushes or continuously. According to Moritz, who watched the process through a duodenal fistula, 500 c.c. of water may go from the stomach into the intestine in thirty minutes.[14] Similar results have also been reported by other observers who have studied the exit of water.[15] Physiological salt solution likewise may go out rapidly.[16]

Water and salt solution are, of course, very different in consistency from the foods ordinarily taken into the stomach. Furthermore, water and salt solution neither present the conditions for psychic secretion (they are not chewed with a relish, they are swallowed rapidly, they do not satisfy appetite), nor, once in the stomach, do they produce any considerable secretion of gastric juice. When only 100 or 150 c.c. of water are injected, very often not the least trace of secretion occurs. "It is only a prolonged and widely-spread contact of the water with the gastric mucous membrane which gives a constant and positive result (secretion)."[17] The rapid exit of water from the stomach would preclude the conditions which make it even a feeble stimulant of gastric secretion. And the failure of water to excite any noteworthy amount of gastric juice favours a rapid exit, so far as the duodenal reflex is concerned, for the acid stimulus closing the pylorus is thereby absent. Within the stomach, water certainly has an effect on the pyloric sphincter very different from foods which evoke an abundant flow of gastric juice. When such foods are given, scores of peristaltic waves may sweep up to the pylorus before the sphincter relaxes ; but when water is given, it begins to leave the stomach at once.* The

* The quick exit of water, before it is acidified, doubtless explains the readiness with which it conveys infection.

fact that water may pour through the pylorus in a fairly continuous stream, as rapidly as it is swallowed, points definitely to a diminished pyloric tonus. This fact and the failure to stimulate gastric secretion are, as I have pointed out, apparently related to each other. In these facts may be found a probable explanation of the rapid discharge of water from the stomach.*

In the same class with water is raw egg-white. In my observations on the rate of discharge of different foods from the stomach, I pointed out that egg-albumin formed an exception to the general rule that protein passes out from the stomach slowly.[18] This observation is confirmed by London and Sulima's study of dogs with a duodenal fistula. They found that raw egg-albumin begins to pass the pylorus immediately after ingestion; it emerges in large gushes at intervals of four or five seconds. These gushes are therefore too frequent to correspond to the occurrence of peristaltic waves. For about twenty minutes the egg-white issues from the stomach with an alkaline reaction; then the reaction becomes acid, and the discharge naturally is more seldom (one to three minute intervals) and less abundant.[19] In this connection it is of interest that Pawlow found fluid egg-white no more effective in exciting gastric secretion than an equal volume of water.[20] Like water, fluid egg-white does not offer the conditions for arousing psychic secretion; and again, attending that condition, there is a state of diminished pyloric tonus, as evidenced by discharges through the pylorus much more frequent than the peristaltic waves in the dog's stomach. The rapid passage of fluid egg-white from the stomach would therefore be

* Cohnheim states that water swallowed by dogs when the stomach is full passes along the lesser curvature, through a little channel formed there, and, diluting only the contents of the vestibule, pours through the pylorus. After the first few gushes the water appears at the duodenal fistula, free from gastric contents, and almost neutral in reaction (*München. med. Wchnschr.*, 1907, liv., p. 2582). I have some tracings made in 1898, showing how water containing bismuth, when swallowed into a full stomach, leaves the bismuth lying along the lesser curvature. It occurred to me then that this phenomenon in a carnivorous animal was not unlike the course of the more fluid food in ruminants; but as I had no further evidence, I did not call attention to the observation. The strong, oblique fibres of the inner muscular coat (see p. 47) would help to make a channel by their contraction. There is not, however, entire agreement among observers on the passage of water through the stomach during gastric digestion. Leven and Barret have found that, whereas water disappears rapidly from the resting stomach, its discharge is considerably retarded if taken with food, even with a few bites of bread (*Radioscopie Gastrique et Maladies de l'Estomac*, Paris, 1909, p. 75). Of course, the delay under these circumstances is readily explained.

explained in the same manner that the rapid outgo of water is explained.*

According to my earlier investigations, egg-white coagulated by heat also left the stomach at a rapid rate. This observation, likewise, is confirmed by London and Sulima. They found, however, that, unlike fluid egg-white, the coagulated form did not begin to leave the stomach immediately, but several minutes after ingestion. When the gastric discharge began, its reaction was acid. First the discharge had only fine particles of the egg-albumin, but later these were much larger.[21] These unchanged particles are significant, for they indicate that the acid has been secreted more rapidly than it could unite with the compact coagulum of the egg-albumin.[22] This failure of the acid to unite with albumin as soon as secreted brings about the same condition that prevails when carbohydrates are fed: there is an early appearance of free acid in the stomach. London and Sulima reported large amounts of free hydrochloric acid in the chyme of coagulated egg-white.[23] On the other hand, although the chyme of beef and fibrin is acid in reaction, it may not contain free hydrochloric acid (see p. 104). This difference in the rapidity of union with the acid as it is secreted would account for the difference in the rate of discharge of these proteins. The slow union of acid with coagulated egg-white, and the resultant early appearance of free acid in the stomach, explains the rapid departure of this food.

That water does not emerge rapidly from the stomach merely because it is fluid was shown by the observations of Moritz.[24] Weak hydrochloric acid, he found, passed out more slowly than water, and beer passed out with even greater retardation. The slow exit of weak hydrochloric acid can be explained by its effect in closing the pylorus from the duodenal side. And beer, stimulating gastric secretion not only by its alcohol content,[25] but also by its bitter taste,[26] must go out slowly, because of the acid control of the pyloric passage.

In connection with the acid control of the pylorus the effect of hyperacidity may be considered. By requiring a longer time for neutralization in the duodenum, and thereby holding the pylorus closed for longer periods, hyperacidity might be expected to cause a retardation of gastric discharge. In work with C. A. Hedblom,

* A very rapid exit of a rice preparation moistened with sodium bicarbonate (which hinders gastric secretion) may be similarly explained.

evidence on this question was obtained by feeding potato with which had been mixed a known percentage of hydrochloric acid. The results are represented in the curves of Fig. 16.

In comparing with the standard rate the results of feeding acid food, it is fairer to use the second rather than the first half-hour of the standard curve, since at the beginning of the first half-hour digestion has not begun and no acid has yet appeared at the pylorus, while at the beginning of the second half-hour acid chyme is being discharged. As the curves indicate, the rate of exit is faster than normal when the potato has an acidity of 0·25 per cent., and slower than normal when it has an acidity of 1 per cent. Potato with an acidity of 0·5 per cent. is discharged during the first half-hour about as rapidly as the food is normally discharged. The difference between the outgo of the weakly acid (0·25 per cent.) and the strongly acid (1 per cent.) potato is remarkable. Note that at the end of the first half-hour there was in the intestine more than 2·5 times as much, and at the end of an hour about two times as much, of the weakly acid potato as of the strongly acid. According to Katschkowski, a hyperacidity, even 0·7 to 0·8 per cent. of hydrochloric acid, produces a lasting spasm of the pylorus.[27] Although in our experiments we did not note so pronounced an effect, we found nevertheless that the hyperacidity caused a retardation of the passage of food from the stomach, a result explained by reasons already stated.

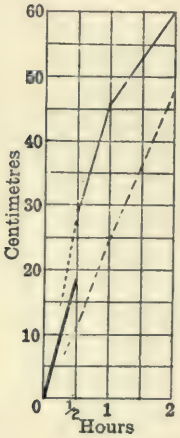

Fig. 16.

The heavy line is the curve (for the second half-hour) when potato is fed normally; the light line, when fed with 0·25 per cent. acidity (HCl); and the dash line, when fed with 1 per cent. acidity.

Some of the other conditions affecting gastric discharge, which Hedblom and I studied, were the consistency of the food, the presence of gas in the stomach, the temperature of the food, and irritation of the colon. The results can be briefly stated.

To obtain information regarding the effects of varying consistency and other mechanical factors on the gastric discharge, observations were made on more or less viscous samples of potato and on hard particles mixed with the food. Before diluting the potato, it was baked, in order to drive off most of the water.

Two series of observations were made. In the first series no water was added; the potato when mixed with bismuth subnitrate and ready for feeding was very thick and doughy. In the second series water was added until the mixture was of the consistency of thin gruel. The volume fed in all cases was 25 c.c. The results with these extremes should be compared with the results when potato of the standard consistency (intermediate between the extremes) is fed. As the curves in Fig. 17 (A) show graphically, the rates of discharge of the same kind of carbohydrate food, thick or diluted, are nearly the same; indeed, the rates of discharge do not differ among themselves enough to

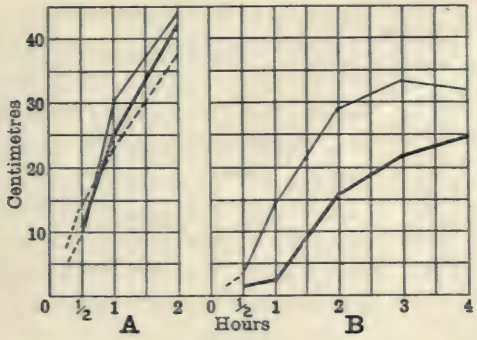

FIG. 17.

A. The light continuous line is the curve for potato of standard consistency; the heavy continuous line, for thick, doughy consistency; the dash line, for thin, gruelly consistency—5 cases each.
B. The heavy line is the curve for lean beef of standard consistency; the light line, that for lean beef of thin, gruelly consistency.

permit any noteworthy significance to be attributed to the varying consistencies.

The dilution of protein food might be expected to have a different effect from the dilution of carbohydrate. If protein food is diluted with water, evidently, in a given amount, less protein is present to unite with acid than would be present if the same amount were given undiluted. To test this supposition, lean beef was fed after being shredded and mixed with water to a thin, gruelly consistency. A comparison of the curves in Fig. 17 (B) shows that the dilution of the protein food, and the reduction thereby of the material uniting with the acid of the gastric juice, tends toward a more rapid discharge of the protein from the stomach.

The factor of consistency of protein food is important in relation to the differing results reported by different investigators. Thus, Cohnheim found,[28] by observations through a duodenal fistula, that the emptying of the stomach began about fifteen minutes after feeding a dog finely chopped meat mixed with water, and Lang reported that the first slight discharges of gastric contents did not occur until at least fifteen minutes after feeding his dogs 200 grammes of fibrin. Moritz, on the other hand, who also used the fistula method on dogs, observed that the exit of the gastric contents began about three-quarters of an hour after feeding 200 grammes of raw meat. My own experience with proteins of standard consistency accords with that of Moritz. The discrepancy between the concordant observations of Cohnheim and Lang and the concordant observations of Moritz and myself is probably due to a difference in consistency of the protein food. Certainly, my results were well within the limits set by Moritz, and did not show nearly so long a delay in the first discharge of meat from the stomach as was reported by Roux and Balthazard.[29]

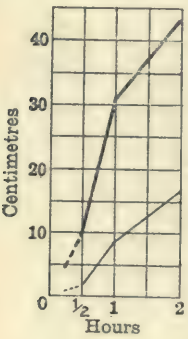

FIG. 18.

The heavy line is the normal curve for potato; the light line, the curve when hard particles are present in the food —10 cases.

Few observations as to the relation between hard food-masses and gastric discharge have been reported. Moritz[30] found in experiments on a dog with a duodenal fistula that finely chopped sausage began to leave the stomach in forty-five minutes, whereas coarse unchopped sausage did not begin to leave for two hours. In my first paper on the stomach[31] I reported that hard particles repeatedly pushed up to the pylorus checked the outgo of food from the stomach. Since improved methods permitted a careful testing of this statement, Hedblom and I repeated the observations, giving small irregular pieces of dried starch paste with the standard potato.

In Fig. 18 the normal discharge is compared graphically with the discharge when the same food, with hard particles added, was fed. There is a marked retardation of the outgo of food from the stomach when hard particles are present.

Food finely divided is sometimes fed in order to spare the

stomach. That results not easy to anticipate may follow was shown by Cohnheim's observations on a dog with a duodenal fistula. The stomach emptied itself of 50 grammes of finely divided meat in an hour and thirty-five minutes. When the same amount was given in large lumps, the stomach required almost an hour longer to empty itself. The coarser meat, however, was discharged almost entirely dissolved, whereas nearly half of the finely divided meat emerged in unbroken particles. As Cohnheim pointed out, the "easily digested," finely divided meat did indeed spare the stomach, but it placed more work in the small intestine.[32]

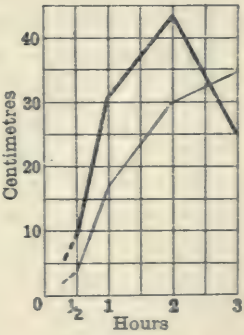

FIG. 19.

The heavy line is the normal curve for potato; the light line, that for potato when gas is present in the stomach.

The usual presence of gas in the fundus of the human stomach has already been mentioned. When a person reclines, this gas of course changes location; and if the person lies on his back, the gas takes a position under the anterior surface of the stomach. That the presence of a body of gas in the stomach might affect the exit of food has apparently not been much considered. Yet with the X rays peristaltic waves can be seen moving over an accumulation of gas without either churning the contents or propelling them onward. The gas acts as a shield, keeping the walls of the stomach away from the food. We desired to learn how a considerable amount of gas in the stomach might effect the discharge.

The animals were first fed the standard amount of food. Air was then introduced into the stomach while the animals were under observation; thus the distension of the stomach walls could be easily regulated. In a few instances eructations nearly emptied the stomach during the first hour; more air was then introduced until approximately the original volume was restored.

The average figures for fourteen cases are compared with the average figures for normal conditions in Fig. 19. As was to be expected, these average figures cover a wide variation in the effects produced by the presence of gas. In few cases, however, was there any effect except a retardation of the discharge into the intestine. This result has been noted repeatedly in other

instances in which gas appeared in the stomach spontaneously. Thus, in one case in which fibrin was fed, and in which the peristaltic waves could be clearly seen passing over the gas in the stomach, the discharge was as follows :

Hours after feeding	½	1	2	3·0	4·0	5
Centimetres of fibrin when gas was present ..	0	0	0	10·0	17·0	22
Centimetres of fibrin, average of four normal cases	4	8	21	29·5	32·5	32

Such cases of spontaneous accumulation of gas seemed to be associated with atony and enfeebled peristalsis. When the air was experimentally introduced, however, peristalsis, when observed, was normal in rate and intensity.

With peristalsis normal, how may the retardation of the discharge, noted in the above experiments, be explained ? That the distension of the stomach walls prevented them from exerting a direct propelling action on the food was distinctly visible. Only at one surface was there contact of the wall with the food. Since gas slips to and fro more readily than fluid or semi-fluid contents, it prevents the normal action of the peristaltic waves. The retardation due to gas is a result which evidently might be different in man and in the cat. In the upright position of man any gas in the stomach naturally rises to the fundus, and the food then lies in the region of active peristalsis. But in the prone position of man gas in the stomach may interfere with peristaltic activities quite as much as it does in the cat.

Observers who have studied the effects of heat and cold on the motor functions of the alimentary canal have reported various results. Lüderitz[33] exposed the stomach and intestines of rabbits in a bath of normal salt solution which was gradually cooled. He saw no change until a temperature of 28° to 30° C. was reached—below 28° the movements gradually ceased. Oser [34] states that low temperatures close the pylorus, but that higher temperatures, up to 37° C., have no such effect. According to Müller,[35] low temperatures have a quieting, even a paralyzing effect on the movements of the stomach, whereas high temperatures increase gastric peristalsis. These statements accord with the observation of Schüle,[36] and Leven and Barret,[37] that warm water leaves the stomach much faster than cold ; but they do not seem to accord with Müller's own results that both hot and cold fluids leave the stomach more slowly than fluids at body temperature.

In such studies the time required for the equalization of the

ingested food to the temperature of the body is important, for probably the temperature effects diminish as the equalization takes place. By use of maximum thermometers, Winternitz[38] observed that thirty minutes after drinking 500 c.c. of cold water the temperature of the gastric contents was only 0·6° C. lower than general bodily temperature. On a patient with gastric fistula, Quincke[39] obtained similar results when cold water was taken, and further found that water at 40° C. reached body temperature within ten minutes. According to Quincke, hot or cold water reaches body temperature sooner than lukewarm milk. As Müller points out, the stomach is in a high degree able to bring food of widely differing temperature quickly to the temperature of the body, a function doubtless dependent on the central position of the organ in the body and on the rich blood-supply in its walls and in the surrounding structures.

Since the stimulating influence due to variations of temperature is present for only a comparatively short interval, the influence exerted might be correspondingly short; but the possibility of the effect outlasting for some time the period of stimulation must be considered. In the following experiments to determine the rate of discharge of hot and cold solid foods, the conditions of experimentation were quite normal. Care was taken to keep the food at the temperature stated until all had been fed.

In two cases in which the hot food was given, the potato was kept in a dish surrounded by a large quantity of water at 50° to 55° C. during the period of feeding, and the animals were fed from a spoon. In the other cases the food was given by means of a syringe, and was delivered into the stomach at a temperature of approximately 60° C. The cold food was fed in a frozen condition, and reached the stomach in frozen lumps.

The only change from the normal in the rate of discharge of food, hot or cold, was a slight acceleration, but this change was so slight as to be inconsiderable. In none of the cases was there observed any notable variation from the usual peristalsis.

In a series of X-ray observations made by C. R. Metcalf, hot and cold applications applied from one to forty minutes to the abdomen of healthy cats produced no appreciable alteration in gastric peristalsis. It continued without interruption and without measurable change of rate. These results are quite in harmony with the statement of Lommel[40] regarding his similar experiments on dogs. On the other hand, as Murphy and I have

reported,[41] excessive cooling of the stomach and intestines, by introducing cold sterile salt solution into the abdominal cavity, may be followed by increased activity of intestinal peristalsis. But this is a procedure causing changes of temperature in the bowel too great to be produced by any external applications.

The conclusion seems justified that changes in the temperature of the food do not influence, in healthy animals, for any considerable time, either gastric peristalsis or the rate of discharge from the stomach.

All the statements made thus far regarding the action of the pylorus have had reference to conditions not attended by any

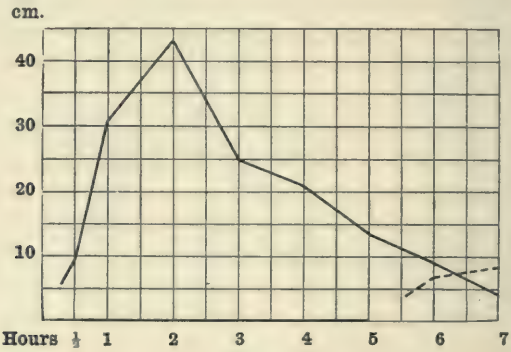

FIG. 20.

The continuous line represents the normal curve for potato ; the dot line, the typical condition immediately following intestinal operation near the pylorus. Gastric peristalsis was seen at every observation after the first half-hour.

pathological change. When pathological states arise, however, the normal action may be profoundly altered.

An illustration of such disturbance of the functions of the pyloric sphincter was given in the observation made by Murphy and myself directly after high intestinal section and suture. Gastric peristalsis was not interfered with, but for almost six hours after recovery from anæsthesia the pylorus remained tightly closed against the peristaltic pressure, and did not permit the food (potato) to pass into the injured gut[42] (see Fig. 20). As we pointed out, there is a remarkable coincidence between the period of delay of the discharge from the stomach and the period required for the primary cementing of intestinal wounds.

Hedblom and I were interested to learn whether any effect on gastric discharge could be demonstrated after causing irritation

of the colon. The irritation was produced by injecting a few drops of croton-oil into the cæcum through a small median incision in the abdominal wall. The operation, performed under ether, did not cause any subsequent signs of discomfort in the animals. The next day they were fed the standard potato, and observed. Comparison of the standard curve for potato with the curve representing the average figures of four cases in which the colon was irritated (Fig. 21) shows at once noteworthy differences. Not only was the gastric discharge much slower when the colon was irritated, but the passage of the food through the small intestine was greatly retarded. The normal curve drops mainly because of the passage of material into the large intestine. When the colon was irritated, the curve failed to drop throughout eight

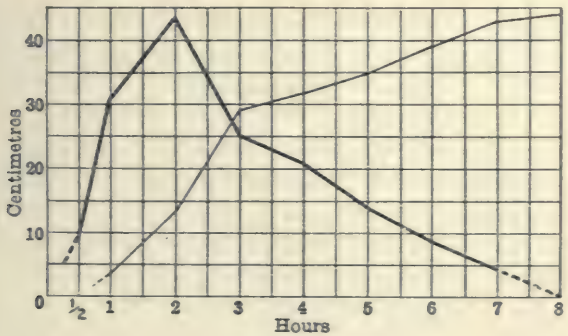

FIG. 21.

The heavy line is the normal curve for potato; the light line, the curve after croton-oil has been injected into the colon.

hours, whereas the normal curve begins to drop at the end of two hours. Normally, potato begins to appear in the colon at the end of two or three hours; under the conditions of the present experiment, however, it did not appear in the colon until six or seven hours had elapsed. In all cases food was still present in the stomach at the end of seven hours, though normally the stomach is emptied of most of this food in about three hours.

Whether injury to the upper small intestine, and irritation of the colon, affect gastric evacuation through an alteration of gastric secretion has not been ascertained. There are pathological conditions of the stomach, however, in which gastric secretion is disturbed, and in which the acid control of the pylorus certainly is in abeyance. Cohnheim has described a dog which,

though recovering from gastric catarrh and possessed of a good appetite, still secreted no gastric juice. When meat was fed, it passed through the pylorus in a short time wholly undigested. Thus the small intestine was overwhelmed with a mass of unprepared material, and exposed in turn to the possibility of a secondary disturbance of its own functions.[43]

In achylia gastrica, likewise, the absence of acid does not lead to a retention of food in the stomach ; indeed, it is likely to depart with unusual rapidity. But evacuation in the absence of an acid reaction is only one problem to be settled either in achylia gastrica or in such cases of gastric catarrh as that instanced by Cohnheim. Pancreatic secretion without the natural acid stimulus in the duodenum needs quite as much to be investigated and explained.

As shown by these examples, only after the discovery of natural relations is the character of disturbed relations revealed. If in spite of disturbed relations the processes concerned continue to be serviceable to the organism as a whole, an adaptation to the new conditions must have occurred. The ability of organs to adapt their functioning gradually to pathological states is well known in many instances. This adaptation, however, must be studied by itself as a special subject. Thus, after the normal physiology of the pylorus is made clear, it becomes of interest to know to what extent and in what manner disturbances in the stomach and duodenum are attended by changes in the pyloric reflex which are compensatory. The fact that compensations may occur is not an argument against the normal functioning. The activities occurring in the pathological absence of gastric juice do not affect the great array of evidence in favour of the normal acid control of the pylorus, just as compensated aortic regurgitation does not prove that the semilunar valves have no function. We are thoroughly justified, therefore, in supporting, by all the favourable evidence here reviewed, the conclusion that acid above opens and acid below closes the pyloric passage.

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CHAPTER XI

THE MOVEMENTS OF THE SMALL INTESTINE

THE longest portion of the alimentary canal is the small intestine. Its relative length varies, however, in different animals, and this variation is related interestingly to the character of the food. Carnivorous animals as a rule have a relatively shorter small intestine than do herbivorous animals. Thus in the cat the tube is about three times the length of the body, in the dog four to six times, whereas in the sheep and goat it may be more than twenty-seven times the body-length.[1] The extensive surface provided by this length of gut is further augmented in many animals by the folds which project inward and form the " valvulæ conniventes." And the mucosa covering the interior of all this surface has its area again enormously increased by being disposed on the finger-like villi, which project inward in countless myriads towards the lumen. Between this vast extent of mucosa and the outer longitudinal and inner circular muscle of the intestine lie venous and lymphatic plexuses, and the radicles of larger vessels belonging to these two systems.

Digestive juices secreted in the mouth, the stomach, and in the duodenum, have already accomplished marked alterations in the food by the time it is pushed on into the ileum. Yet in this extensive region the final changes occur, and while here the nutritious portions of the food are almost completely digested and absorbed. The small intestine, therefore, is the very centre of the essential activities on which the body depends for nourishment.

The mechanical factors of digestion, as we have seen, have the functions of propelling the food, mixing it with the digestive juices, and exposing the digested food to the absorbing mucosa. These functions, all of them of first importance in co-operation with digestion and absorption, are accomplished in the small

intestine by two main types of activity—by the peristaltic wave, and by rhythmic contractions of the intestinal musculature. When an animal is first fastened to the holder, after the food has been distributed through the intestine as shown in Fig. 6, the noteworthy condition in most or all of the loops is the total absence of movement. If the animal remains quiet, however, only a few moments elapse before peculiar motions appear in one or another of the loops, or perhaps in several, and last for some time. These motions consist in a sudden division of one of the long, narrow masses of food into many little segments of nearly equal size; then these segments are again suddenly divided, and the neighbouring halves unite to make new segments, and so on, in a manner to be more fully described. I have called this process the "rhythmic segmentation" of the intestinal

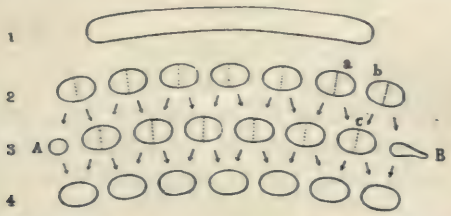

FIG. 22.—DIAGRAM REPRESENTING THE PROCESS OF RHYTHMIC SEGMENTATION.

Lines 1, 2, 3, 4, indicate the sequence of appearances in a single loop. The dot lines represent the regions of division. The arrows show the relation of the particles to the segments they subsequently form.

contents.[2] Further observation reveals peristalsis here and there. These phenomena are now to be considered in detail.

Rhythmic segmentation is by far the most common and the most interesting mechanical process to be seen in the small intestine. The nature of the process may best be understood by referring to the diagram, Fig. 22. A mass of food is seen lying quietly in one of the intestinal loops (line 1, Fig. 22). Suddenly an undefined activity appears in the mass, and a moment later constrictions at regular intervals along its length cut it into little ovoid pieces. The solid string* is thus quickly transformed, by a simultaneous sectioning, into a series of fairly uniform segments. A moment later each of these segments is divided into two particles, and immediately after the division

* In lieu of any better short expression, "string" of food is used to designate the long, slender mass of the contents lying in a loop of the intestine.

neighbouring particles (as *a* and *b*, line 2, Fig. 22) rush together, often with the rapidity of flying shuttles, and merge to form new segments (as *c*, line 3, Fig. 22). The next moment these new segments are divided, and neighbouring particles unite to make a third series, and so on.

At the time of the second segmentation (line 3, Fig. 22) the particles at the ends of the row are left small. Observation shows that these small pieces are not redivided. The end piece at A simply varies in size with each division ; at one moment it is left small, at the next moment it is full size from the addition of a part of the nearest segment, and a moment later is the small bit left after another division. The end piece at B (probably the rear of the mass) shoots away when the end mass is divided, and is swept back at each reunion to make the large end mass again, only to be shot away and swept onward with each recurrence of the constrictions.

The process of repeated segmentation thus continues, with the little particles flitting toward each other, and the larger segments shifting to and fro, commonly for more than half an hour without cessation. From the beginning to the end of a period of segmentation the food is seen to have changed its position in the abdomen to only a slight extent. Whether this change is a passing of the food along the loop, or a movement of the loop itself, it is impossible to tell from the shadows on the screen. The change of position, however, is much less conspicuous than the lively division and redivision which the mass suffers so many times from the busy, shifting constrictions.

From this typical form of rhythmic segmentation there are several variations. Sometimes, and especially when the mass of food is thick, the constrictions do not make complete divisions, and are so far apart that the intermediate segments are relatively large. Moreover, the constrictions do not take place in the middle of each segment, but near one end. In another variety of segmentation the food is divided, and the first divisions then subdivided, before any reunion occurs. This form of segmentation is fairly typical for the constrictions seen in a small mass advancing through the intestine. Sometimes the divisions occur in the middle of a long string of food, and leave the ends wholly unaffected.

A remarkable feature in the segmentation of the food is the rapidity with which the changes take place. The simplest way

of estimating the rate is to count, not the number of times the partition of the food recurs in the same place, but the number of different sets of segments observed in a given period. Thus in Fig. 22 the appearances of lines 2, 3, 4, etc., would be counted, and not merely lines 2, 4, etc. Repeated observations have shown that the rate of division in long, thin strands of food may commonly be as high as twenty-eight or thirty times in a minute —*i.e.*, a change from one set of segments to another set every two seconds, and a return of the same phase every four seconds. In some cases the rate is as low as eighteen to twenty-three times per minute. The larger masses seem to be associated with a slower segmentation.

Segmentation frequently continues for more than half an hour ; in one instance it was seen persisting, with only three short periods of inactivity, for two hours and twenty-two minutes. At the rate of thirty segmentations per minute, it is clear that a slender string of food may commonly undergo division into small particles more than a thousand times while scarcely changing its position in the intestine.

This process, thus far described as I saw it in the cat, I have seen also in the white rat and in the dog.[3] In the white rat the changes occurred at the rate of forty-four to forty-eight per minute ; in the dog, sometimes at a rate between eighteen and twenty-two, at other times between twelve and fourteen, per minute. The segmenting movements I have never seen in the rabbit, but, instead, rhythmic to-and-fro shiftings of a mass along the lumen of the gut, rapidly repeated for many minutes. In 1905 I reported having heard rhythmic sounds in the human intestine at the rate of seven or eight per minute, and gave reasons for believing that this rhythm was caused by segmenting movements.[4] Two years later Hertz was able to observe the process of segmentation in man. " The shadow of the short length of small intestine, at first of uniform thickness, became constricted in its centre ; the constriction increased until the single shadow was more or less completely divided into two. Then each half underwent a similar division, but the two central segments of the four produced by the second division joined together. The new central segment then divided again, the segmentation continuing, in one case, at the rate of ten divisions in a minute and a half."[5] This rate is approximately seven divisions per minute, which is about the rate of the rhythmic sounds which I had heard.

The process of segmentation in cats has been observed also by Hertz [6] and by Magnus,[7] both of whom used the X-ray method ; and it has been seen in dogs with opened abdomen by Henderson,[8] who likened the appearance to that which would be presented by a column of large frog-hearts beating in such mutual co-ordination that, while numbers 1, 3, 5, and 7, are in systole, 2, 4, 6, and 8, are in diastole, and *vice versa*. From all this evidence, it is clear that the process is one whose existence is thoroughly well established.

The appearance of the exterior of the small intestine while this process is occurring is shown in Fig. 23. This photograph was taken after the animal, well anæsthetized, had had its spinal cord pithed below the brachial region, and its abdomen opened under warm physiological salt solution. Active digestion was in progress. A noteworthy feature of the rings of constriction, which contrast with the peristaltic wave, is their narrowness. As these narrow constrictions occur the region becomes pale and bloodless.

FIG. 23.—A PHOTOGRAPH OF THE SMALL INTESTINE SEGMENTING ITS CONTENTS.

The effect of the process of rhythmic segmentation proves it an admirable mechanism. The food over and over again is brought into closest contact with the intestinal walls by the swift, kneading movement of the muscles. Thereby not only is the undigested food intimately mixed with the digestive juices, but the digested food is thoroughly exposed to the organs of absorption. Mall[9] has shown that contraction of the intestinal wall has the effect of pumping the blood from the submucous venous plexus into the radicles of the superior mesenteric vein, thus materially aiding the intestinal circulation. Moreover, lacteals loaded with fat will in a few moments become empty unless the intestine is slit lengthwise so that the muscles cannot exert compression.[10] The rhythmic constrictions, therefore, both propel the blood in the portal circulation and act like a heart in promoting the flow of lymph in the lacteals. This single movement, with its several results, is another excellent

example of bodily economy. The repeated constrictions thoroughly churn the food and digestive fluids together, plunge the absorbing mucosa into the very midst of the food-masses, and also, by compression of the veins and lacteals of the intestinal wall, serve to deport through blood and lymph channels the digested and absorbed material.

There is little doubt that segmentation is due to an activity of the intestinal musculature similar to that which causes the so-called "pendulum movement." This activity is characterized by a gentle swaying motion of the coils, and is accompanied by rhythmical contractions. Observers have described it variously as shortenings and narrowings of the gut, rhythmically repeated at nearly the same intestinal circumference;[11] as alternating to-and-fro movements of the long axis without changes in the lumen;[12] as local or extensive periodic contractions and relaxations mainly of the circular musculature;[13] and as waves involving both muscular coats of the intestine, and travelling normally from above downward at a rapid rate (2 to 5 centimetres per second).[14] The pendulum movements have been seen in the dog and in the rabbit and cat.[15] In the cat, Bayliss and Starling noticed that, when the lumen of the gut was distended by a rubber balloon, there appeared rhythmical contractions, which nearly always were most marked at about the middle of the balloon—*i.e.*, the region of greatest tension.

The segmenting movements, of course, do involve changes in the lumen, and they do not appear as waves. In these respects, therefore, they do not fit certain descriptions of the pendulum movements. Segmentation is, however, a local contraction and relaxation of the intestinal musculature; and its occurrence, usually at a point midway between two rings of constriction, where the compressed food stretches most forcibly the relaxed circular and longitudinal muscles, indicates that it is a response to the increased local tension.

The best known of the intestinal movements is the peristaltic wave. It is observed in two forms: as a slowly advancing contraction which creeps through a short distance in a coil, and as a swift movement sweeping without pause for much longer distances along the canal. The first form of the wave merely transports nutriment from one region to another near by, thus utilizing different areas of the mucosa for secretion and absorption; the second form, which may glide swiftly from

one end of the canal to the other, has the effect of clearing it of its contents. The first form may retain the unqualified term *peristalsis ;* the second may be distinguished by the term " rushing peristalsis," or " peristaltic rush," as suggested by Meltzer and Auer.[16]

The normal peristaltic wave is slow. Its rate has been variously stated as 1 or 2 centimetres per minute, or even slower.[17] By most observers the wave is said to move always in one direction—from stomach to colon.

The contraction that occurs in rhythmic segmentation is narrow, involving hardly a centimetre of the circular coat ; the contraction that occurs in peristalsis, on the contrary, extends along the canal for 4 or 5 centimetres. The difference can be clearly seen by comparing Figs. 23 and 24. A much larger number of circular fibres are evidently engaged when food must be pushed through the canal than are active in any single segmenting contraction.

FIG. 24.—A PHOTOGRAPH OF A PERISTALTIC WAVE ON THE SMALL INTESTINE.

The wave was pushing material into the colon.

With the X rays it is commonly impossible to see how a moving mass of food is related to the end of the intestine, and therefore it is impossible to state absolutely whether peristalsis or antiperistalsis is active. The relations can be seen with the fluorescent screen only near the stomach and near the ileo-colic valve. The evidence that advancing peristalsis alone occurs normally is, as we shall see, so overwhelming that we can safely assume that, when food is moving in loops not visibly related to fixed points, it is moving onward.

When a mass of food has been subjected for some time to the segmenting activity of the intestine, the separate segments, instead of being again divided, may suddenly begin to move slowly along the loop in which they lie. That this movement is not a swinging of the coil as a whole, but a peristaltic advance of separate rings of its circular musculature, is made probable by the fact that the succeeding segments follow along the same path their predecessors have taken. The advance of the little

pieces may continue for 7 or 8 centimetres, when finally the front piece stops or meets other food. Then all succeeding pieces are swept one by one into the accumulating mass, which at last lies stretched along the intestine, a solid string manifesting no sign of commotion.

Another form of slow peristalsis is frequently observed when the food is pushed forward, not in small divisions, but as a large lump. The relatively long mass of food is first crowded into an ovoid shape as the forward movement begins. The next moment it is indented in the middle by a circular constriction, which spreads it into two portions along the loop. Now both portions may be cut in two. The whole mass is at once swept together again, and slightly beyond its first position, whereupon the segmenting process is repeated. Thus, with many halts and interruptions, the food slowly advances.

A slight variation of the combined peristalsis and segmentation just described is seen when the amount of food is greater and extends farther along the intestine. Under such circumstances, as the mass moves forward, there appears just in front of the rear end, where the distension is greatest, a constriction which separates a piece from the main body, and causes it to shoot backward sometimes through the distance of a centimetre. The main body meanwhile is not disturbed. No sooner has the rear section been shot away than it is swept forward again into union with the rest of the food, and the whole mass then advances until another interfering constriction repeats the process.

Peristalsis may become disturbed after a surgical operation requiring the intestine to be severed and sutured. Clinical experience has not determined whether end-to-end or lateral methods of uniting the divided intestine are preferable. In favour of the lateral junction, the argument has been urged[18] that it permits conveniently a desirable large contact of serous surfaces—a condition said not to be possible in the end-to-end union without dangerously narrowing the lumen of the canal, and without liability of producing death of the tissues from pressure on mesenteric vessels. The claims have been made, also, that lateral anastomosis can be used without regard to the size of the intestinal parts to be united, and that with it the opening between the two intestinal ends can be made as extensive as may be wished. On the other hand, the tendency of all lateral unions of parts of the alimentary canal to become nar-

rowed has been repeatedly recognized. And studies on animals have shown that indigestible substances, such as straw and hair, may accumulate at the point of lateral union and block the passage.[19] Such a condition, however, has never been cited as true of man whose diet is carefully watched after operation.

Theoretically there are possibilities of functional defect both in the end-to-end and in the lateral union. In the end-to-end junction two severed ends of the intestine are sewed together. The transverse cutting of the gut destroys locally the mechanism governing peristalsis, and under these conditions there might be stasis of the food in the region of union. In lateral anastomosis circular muscle fibres of the canal are cut—the fibres which force the food onward. Contraction of the circular muscle singly in either one or the other of the overlapping intestinal ends cannot then force the food onward, but must simply shift the food over into the inactive part. For propulsion of the contents of this region there must be a co-ordinated, advancing contraction of the circular fibres simultaneously in the two apposed loops. Undigested material is commonly found as a remnant in the region of lateral junction. Is there in this region a stasis of the normal food material ?

In order to test the possibilities of functional disturbance, F. T. Murphy and I made intestinal sections and resections in animals, and then united the severed gut either end-to-end or laterally. For two reasons the operation was performed as near as possible beyond the delicate fold of mesentery which holds the end of the duodenum in place : the point is fixed so that the position of the suture can be recognized fairly accurately in observations with the X rays ; and it is so near the stomach that the observer does not have to wait long after feeding the animal before the food reaches the region he wishes to study.

Observations were made on different animals one, four, seven, and ten days after end-to-end union of the intestine. In no case was the slightest evidence observed of stasis of the food in the region of operation. The food was passed along that part of the intestine as it was passed along other parts.

The results were quite different with lateral anastomosis. Animals permitted to live ten days or two weeks showed usually the condition already mentioned—a more or less complete blocking of the canal by accumulated hair and undigested detritus at the opening between the apposed loops. To see

whether there was a stoppage of the normal food at the anastomosis, animals were operated upon and carefully fed for four days on food with little waste. Then they were given a rather thin boiled starch (4 grammes of starch to 100 c.c. of water), with an admixture of bismuth subnitrate. As long as this food was passing through the intestine, some of it was always present at the junction. And when almost all the unabsorbed material was in the colon, there still remained a large mass filling the widened lumen where the coils were laterally joined. Observation the next day showed the mass still at the anastomosis. Autopsies on these animals proved that the stasis of the food was not due to previous accumulation of indigestible waste. The region of junction was filled, not with hard material, but with a pasty stuff, in physical characteristics much like that seen ordinarily in the small intestine, and certainly capable of easy peristaltic transportation through the gut. In these cases the two apposed coils evidently did not co-operate to propel the enclosed food. Any food forced through the region of union was propelled by a push from behind, a push exerted by peristalsis of the intact wall driving new masses from time to time into the accumulation at the junction. And when no food remained to act as an intermedium between the accumulated mass in the widened lumen and the pressing peristalsis of the intact gut, there was nothing to continue the propulsion through the common chamber, and the mass was left unmoved.

Inasmuch as stasis was not observed at any time after end-to-end union of the severed gut, whereas after lateral anastomosis ordinary food was stagnant in the region of junction, it is clear that, other things being equal, the end-to-end union is preferable to the lateral for rapid return of the normal functioning of the canal. In time after lateral union the canal may become changed from a crooked to an almost straight tube.[20] As such an alteration takes place, possibly there occurs a restitution of the functional efficiency of the joined parts. The absence of this functional efficiency, however, certainly for some days, and probably for weeks, after the operation, renders lateral anastomosis not an ideal procedure. The dangers of the end-to-end union, on the other hand, have been largely obviated by recent improvements in the technique of intestinal surgery.

As to the claim made for lateral anastomosis, that it permits the opening between the two intestinal ends to be as large as

desired, we must recognize that the more extensive the cutting of the circular muscle, the greater is the interference with peristaltic activity; and also, that the condition to be desired is not so much a large opening as an opening that functions satisfactorily.

Although our experiments led us to differ from the opinion of Ashton and Baldy,[21] that lateral union is always desirable, we agree with them as to the danger of allowing the blind ends of the intestinal loops in lateral union to extend beyond the anastomotic opening. If each extends beyond the opening, the end of the proximal loop, in our experience, is in danger of becoming packed with hardened waste, and the end of the distal loop is likely to invaginate until the invaginated portion fills the lumen in the region of the anastomosis, and produces obstruction (see Fig. 25).

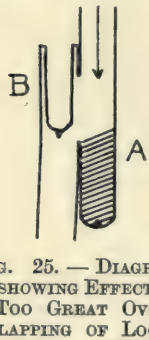

FIG. 25. — DIAGRAM SHOWING EFFECT OF TOO GREAT OVERLAPPING OF LOOPS IN LATERAL UNION. Proximal loop (A) impacted, distal loop (B) invaginated.

The blocking of the lumen in our experiments, when the intestine was united laterally, led us to make observations on the movements of the canal in case of obstruction. Even when the obstruction was within 25 centimetres of the pylorus, it did not retard the discharge of food from the stomach. As the food collected in the obstructed gut, there was seen in every instance a remarkable exhibition of intestinal activity. Ordinarily in the small intestine, as I have stated, segmentation is a much more common activity than peristalsis. Over and over again, however, in these cases of obstruction, the food was pushed toward the obstruction by repeated waves of peristalsis. Nothnagel reported[22] increased activity of like character above an experimental obstruction in the small intestine of the rabbit. The moving constrictions in our cases were evidently powerful, for as they advanced, the walls of the canal in front were bulged widely by the compressed contents; and when the peristaltic ring could no longer withstand the pressure it was causing, the contents squirted back through the advancing ring for some distance along the gut. No sooner had one wave passed over the accumulated food to the point of blocking than another would start and go over the same course again, or a series of rhythmic contractions would occur, dividing the contents into

large segments, and sometimes separating them widely from one another. The numbered parts in Fig. 26 are tracings of the sequence of changes in the shadows of the food during a few moments of observation about an hour and a half after feeding boiled gluten-flour. Similar activities, though not so violent, were seen an hour previous. Other cases, observed during a longer period, showed this same vigorous squeezing and churning of the accumulated food, alternating, however, with periods of rest.

From these observations it is clear that, when the intestine is obstructed, an activity is aroused which must tend to com-

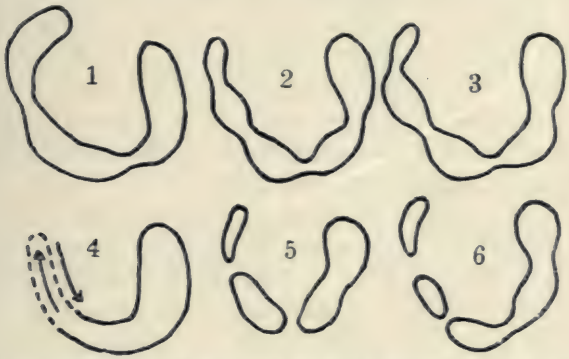

FIG. 26.—TRACINGS OF THE SHADOWS OF THE CONTENTS OF AN OBSTRUCTED LOOP OF INTESTINE, SHOWING THE SEQUENCE OF CHANGES THROUGH SEGMENTATION AND PERISTALSIS DURING A FEW MOMENTS OF OBSERVATION ABOUT AN HOUR AND A HALF AFTER FEEDING.

In the condition represented by No. 4 there was repeated peristalsis, with regurgitation of the food through each advancing peristaltic ring.

pensate for the obstruction, and work to obviate it. These results support the contention made in the discussion of gastro-enterostomy, that kinks and sharp bends in the intestine normally have food forced through them by peristalsis. A kink was artificially produced by turning a loop back on itself for about 4 centimetres, and sewing together the surfaces in contact. Observation five days later proved that the food was pushed around the very sharp bend of the tube by the vigour of the peristaltic waves.

The possibility of waves moving in either direction along the gut anyone can readily prove by repeating Engelmann's observation on the intestine of an animal recently killed.[23] To what

extent the conditions in reversed loops may become similar to those in the dead animal is not known. That antiperistalsis does not occur in the small intestine seems to be proved by Mall's experiment[24] of reversing a portion, sewing it in place, and then finding that undigested material did not pass the reversed region, but collected at the upper end. Other observers,[25] after reversing various lengths of the gut, have confirmed Mall's conclusion that peristalsis does not reverse in the reversed portion, but they have found further that thoroughly digestible food can be pushed through reversed loops, when not too long, without any noticeable difficulty. The addition of solid indigestible stuff, such as pieces of straw and bone, at once caused stasis at the upper junction.

Opposed to the conclusion that there is no antiperistalsis of the small intestine is the clinical evidence that in cases of intestinal obstruction continued vomiting of offensive decomposed material may occur after the stomach has been repeatedly washed—the so-called "fæcal vomiting."

In relation to this conflict of evidence, our observations on an animal with about 20 centimetres of the intestine reversed just beyond the duodenal band are of interest. The first observation was made six days after the operation. At the autopsy not long thereafter, a heap of indigestible stuff was found obstructing the canal at the upper suture. With the X rays the food had been seen again and again leaving the stomach. After collecting in the duodenum, it moved onward, with occasional segmentation, through a definite course which was traced on transparent paper. Finally it began to accumulate in the region of the upper suture. About a half-hour after ingestion the whole mass began to be tossed about by the alternating periods of segmentation and peristalsis characteristic of the state of obstruction. Suddenly the mass was divided near the enlargement of the upper suture; then the proximal portion was moved rapidly back along the course which had been traced, even up to the pylorus. This reversed movement of the food was seen repeatedly with perfect distinctness. The method used did not permit seeing the contractions of the intestinal wall; only the effects on the food could be observed. But if food had been moved forward, as in this instance it was certainly moved backward, the movement must assuredly have been attributed to peristalsis.

Further evidence of the possibility of antiperistalsis in the small intestine has been brought forward by several observers who, some time after the operation, have watched directly the activities of a reversed part of the gut. More than three months after operation, Kelling saw in the exposed intestine the contents moved towards the colon through the reversed portion by distinct peristaltic waves.[26] Enderlen and Hess were able to produce downward peristalsis in a reversed loop by electrical stimulation.[27] And after a considerable interval had followed the reversal, Beer and Eggers,[28] and McClure and Derge,[29] reported seeing peristaltic waves moving distinctly from the upper to the lower junction. In time, therefore, conditions may arise which alter the function of the intestinal wall.

The swift wave of peristalsis that may sweep over the entire length of the small intestine in about a minute, or over extensive reaches of the gut, was observed first by v. Braam-Houckgeest [30] in rabbits with exposed intestines, killed by asphyxia. The confused turnings and squirmings of the coils as the contraction rushes along have caused the phenomenon to be designated as "Rollbewegung" and the "vermicular wave." As already stated, Meltzer and Auer have suggested the term "peristaltic rush"—complete or incomplete, according as all or only part of the small intestine is involved.

This peculiar type of intestinal activity Starling was inclined to regard as an exaggeration of the rhythmic type[31]; on the other hand, Mall placed it in a class by itself and declared that its service was to rid the intestine rapidly of irritating substances. That this rushing wave is, however, truly peristaltic in character was proved by the observation of Meltzer and Auer, that it consists of a contraction preceded by a completely relaxed section of the gut, through which the contents are rapidly driven. They were able to evoke the phenomenon at will in rabbits by intravenous injections of pairs of substances producing stimulation and inhibition of intestinal activity. The most effective pair was ergot (stimulant) and calcium chloride (depressant).[32]

Peristaltic rush probably occurs in conditions of abnormal irritation of the gut, and may be the characteristic activity when a purge is given. With the X rays I have seen rapid peristalsis produced in the small intestine by injecting an enema of soapsuds. Under normal conditions, the only similar occurrence of rapid peristalsis is that frequently observable when food, after being

segmented in the duodenum, is carried swiftly onward through a number of coils before being released.

Having considered the motor activities exhibited by the small intestine, we may now turn our attention to the mechanical treatment which the food receives in traversing it. As we have learned, the chyme is not forced from the stomach by every wave that passes over the vestibule, but only at intervals. When the pylorus relaxes, the food, under considerable pressure, is squirted along the duodenum for 2 centimetres or more. Careful watching of this food shows that usually it lies for some time in the curve of the duodenum, until, with additions from the stomach, a long, thin string is formed. While resting in this place it is exposed to the outpouring of bile and pancreatic juice. All at once the string becomes segmented, and the process continues several minutes, thoroughly mixing the digestive juices with the chyme. In this region the alternate positions of the segments are sometimes far apart, and the to-and-fro movement of the particles may be a relatively extensive and very energetic swinging. Finally, the little segments are united into a single mass, or formed in groups, and begin to move forward. Peristalsis here, as already mentioned, is much more rapid than normal peristalsis elsewhere in the small intestine. The masses, once started, go flying along, turning curves, whisking hither and thither in the loops, moving swiftly and continuously forward.* After passing on in this rapid manner for some distance, the food is collected in thicker and longer strings, resembling the strings seen characteristically in the other loops. Towards the end of digestion, the small masses shot out from the stomach, after a few segmentations, may move on in the rapid course without being accumulated in a larger mass until the swift movement ceases.

During the first stages of digestion in the cat's small intestine the food usually lies chiefly on the right side of the abdomen; during the last stages the loops on the left side usually contain the greater amount of food. In these loops the food remains sometimes for an hour or more with no sign of movement. All at once a mass may begin to undergo division and reunion, division and reunion, over and over again, in the manner described above as rhythmic segmentation. After a varying length of time the activity wanes, and the little segments are carried forward

* If this process is true also of man, the region beyond the duodenum would naturally be "jejune."

individually and later brought together, or united and moved on as a single body, or left quietly for some time without further change. Thus by a combined process of kneading and peristaltic advance the food is brought to the ileo-colic valve to enter the large intestine.

In studying the passage of food through the small intestine of a woman with a fistula at the ileo-colic junction, MacFadyen, Nencki, and Sieber,[33] noted a considerable variation in the time between the ingestion of the food and its appearance at the fistula. Peas, for example, arrived at the colon on one occasion two and a quarter hours, and on another occasion five and a quarter hours, after being eaten. Demarquay,[34] who studied a case similar, but apparently less normal, reported also a wide variation in the time of the first appearance of food at the fistula.

The X-ray method as I used it did not permit a statement of the moment when the food first entered the colon ; only the first regular observation after food had entered could be reported. Since the observations were an hour apart, the results, except in their negative aspect, were not as exact as could be desired. The following figures, therefore, represent for each foodstuff the number of cases in which, at the hours stated, a shadow was first seen in the colon :

Hours after feeding	2	3	4	5	6	7	8*
Carbohydrates (sixteen cases) ..	1	6	4	4	—	1	—
Proteins (sixteen cases)	—	1	2	2	7	2	2
Fats (sixteen cases)	—	2	3	7	2	2	—

This table indicates a variation similar to that observed in man. Although the mean time after eating at which material reaches the colon is about four hours for carbohydrates, about six hours for proteins, and about five hours for fats, the divergence from the mean in each of the three cases is considerable. Among the carbohydrates used, the divergence was chiefly due to moistened crackers, which in four instances arrived at the colon only after five or seven hours. And among proteins, also, the divergence was chiefly due to one food—boiled haddock—which reached the colon about two hours earlier than most of the other proteins. As a general statement, we may say that in the cat carbohydrates reach the large intestine about one hour before fats, and about two hours before proteins. After time is allowed for the later

* In two cases no material had reached the colon at the end of seven hours ; they are regarded as belonging to an eight-hour class.

start of proteins from the stomach, the probability still remains that proteins pass through the small intestine much more slowly than do carbohydrates, whereas fats have a rate intermediate between the two.

The relatively rapid movement of carbohydrates through the canal may be associated with the presence of insoluble cellulose. Hedblom and I found that coarse, branny food stimulates gastric peristalsis; it also passes through the small intestine with unusual speed. In X-ray observations on man, Hertz noted that after an ordinary meal a shadow appeared in the cæcum after intervals varying between three and a half and five hours, with an average interval of four hours and twenty-two minutes.[35] When a horse eats oats, the waste may go through the much longer intestine of that animal in less time.[36] The greater length of the small intestine in herbivorous animals compared with carnivorous, mentioned at the beginning of this chapter, is possibly associated with the greater rapidity of movement of plant food and the necessity of digesting out the valuable contents from cellulose surroundings.[37]

In experimental animals I have never seen any marked delay in the passage of food through the small intestine except under experimentally disturbing conditions, such, for example, as irritation of the colon (see p. 127). Hertz has reported that, in his observations on human beings, delay in the small intestine has occurred only in cases of lead-poisoning. If the evacuation of the bowels is retarded, therefore, and no obstruction of the lumen exists, the chances are almost wholly in favour of the large intestine as the place of retention.

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CHAPTER XII

THE MOVEMENTS OF THE LARGE INTESTINE

In carnivorous mammals digestion occurs principally in the stomach and small intestine ; the cæcum is either rudimentary or absent. In herbivores, as a rule, either the stomach is amplified and subdivided, as in ruminants, or, if the stomach is simple, there is usually compensation in a large sacculated colon and cæcum. The cæcum is the seat of extensive bacterial fermentation ; food rich in cellulose may remain in this region for days, undergoing changes which result in its being utilized by the body.[1] Even when the cæcum is of moderate size or rudimentary, as in the cat, prolonged retention of the material delivered by the small intestine is provided for in the reversed peristalsis which prevails in the proximal colon. Food remnants may have begun to enter the large intestine two or three hours after the food was ingested, and they may have left the small intestine entirely empty at the end of seven hours, and yet be found in part in the proximal colon at the end of twenty-four hours. While stagnating in this region, rich in bacterial flora, the contents are subjected to fermentative decomposition, and the last bit of nutriment here disappears.

The energetic chemical processes occurring in the small intestine demand a fluid medium. By the salivary and gastric glands large amounts of fluid are poured out upon the food. This is augmented by the secretions of the pancreas and liver and the wall of the gut itself. Throughout the small intestine, although water is readily absorbed, the digestive products are maintained in a semi-fluid state. Ease of movement through the canal and ready exposure of the food for absorption are doubtless thereby favoured. When the large intestine is reached, however, and practically all of the serviceable substances have entered the body, the water is no longer necessary. In the proximal colon, therefore, water is also removed.

As the waste is crowded onward into the distal colon, it takes on more and more the peculiar fæcal consistency. According to Roith,[2] the contents of the transverse colon in man are generally as firm as those of the rectum. As these fæcal accumulations are periodically pushed into the rectum they are discharged from the body. The motor activities subserving these various functions performed by the large intestine we shall now consider.

When, in the cat, the large intestine is full, palpation through the abdominal wall will demonstrate that the material in the distal colon usually consists of hard incompressible lumps, while that in the proximal colon is so soft that the walls of the gut can be easily pushed together. The condition of the contents in these two regions seems to indicate a rough division of the large intestine into two parts, and the mechanical activities of these two parts verify the differentiation. In the descending colon the material is gripped by persistent rings of tonic constriction (see Fig. 27). In the ascending and transverse colon and in the cæcum, by far the most common movement is antiperistalsis.

The first food to enter the colon from the small intestine in the cat is pressed by antiperistaltic waves towards the cæcum, and all new food as it enters is also affected by them. The waves follow one after another in a series like the peristaltic undulations of the stomach (see Figs. 28 and 32), beginning at the nearest tonic constriction (Figs. 27 and 32). They rarely run continuously for a long time. When the colon is full it is usually quiet. The first sign of activity is an irregular undulation of the walls, then very faint constrictions passing along the gut toward the cæcum. As they continue coursing over the intestine, they become deeper and deeper until there is a marked bulging between successive constrictions. After these deepest waves have been running for a few minutes, the indentations grow gradually less marked, until at last they are so faint as to be hardly discernible. The final waves are sometimes to be observed only in the neighbourhood of the tonic constriction.

Such a period of antiperistalsis lasts from two to eight minutes, with an average duration of four or five minutes. The periods recur at varying lengths of time. In one instance a period began at 1.38 p.m. and was repeated at 2.6, 2.34, 2.55, 3.15, and at 3.36, when the observation ceased. In another instance a period began at 2.43 p.m., and was repeated at 2.57 and at intervals of

from ten to fifteen minutes thereafter while the animal was being watched.

The waves have nearly the same rate of recurrence as those in the stomach ; about five and a half waves pass a given point in a minute. This rate has proved fairly constant in different cats and

FIG. 27.—RADIOGRAPH SHOWING THE REGION OF TONIC CONSTRICTIONS (DESCENDING COLON) AND THE REGION OF ANTIPERISTALSIS (TRANSVERSE AND ASCENDING COLON).

at different stages in the process of digestion. In one case, however, the waves passed at the rate of nine in two minutes.

The stimulating effect of rectal injections on the movements of the small intestine has already been mentioned. Enemata have also pronounced stimulating action on the antiperistalsis of the colon. Usually, the almost immediate result of a rectal injection

of warm water is the appearance of deep antiperistaltic waves, which often continue running for a long period. In one case, after an injection of 50 c.c. of warm water, the waves followed one after another with monotonous regularity during an observation lasting an hour and twenty minutes.

Two other movements have been observed in the ascending colon, but they are rare appearances. The first of these was a serial sectioning of the contents, noticed in an animal given castor-oil with the food. A constriction separated a small segment in the cæcum; another constriction then cut off a segment just above the first, and with the disappearance of the first constriction the two separated segments united. A third segmentation took place above the second, and the changes occurred again. Thus the whole mass was sectioned from one end to the other, and no sooner was that finished than the process began again and was repeated several times. A slight modification of this movement was observed in a colon containing very little food. The mass was pressed and partially segmented in the manner characteristic of the small intestine, and was thus again and again spread along the ascending colon, and each time swept back into a rounded form by antiperistalsis. The second of the two movements mentioned above consisted in a gentle kneading of the contents. This was caused by broad constrictions appearing, relaxing, appearing, relaxing, over and over again in the same place. When several of these regions were active at the same time, they gave the food in the colon the appearance of a restless undulatory mass. Once a constriction occurred and remained permanently in one place, while the bulging parts on either side of it pulsated alternately, at the rate of about eighteen times in a minute, with the regularity of the heart-beat. Although these phenomena are remarkable, they are not usual, and are in no way so important as the antiperistalsis.

The passage of material through the ileo-colic valve seems to stimulate the colon to activity. As a mass is nearing the valve the large intestine is usually quiet and relaxed (Fig. 28, 4.00), though occasionally indefinite movements are to be observed; and sometimes just before the mass reaches the end of the ileum the circular fibres of the colon in the region of the valve contract strongly, so that a deep indentation is present there. The indentation may persist several minutes; it disappears as the muscles relax just previous to the entrance of new material. The

mass is now moved slowly along the ileum, and is pushed through the valve into the colon. The moment it has entered, a strong contraction takes place all along the cæcum and the beginning of the ascending colon, pressing some of the food onward; and a moment later deep antiperistaltic waves (Fig. 28, 4.03) sweep down from the transverse colon, and continue running until the cæcum is again normally full—*i.e.*, for two or more minutes.

These constrictions, passing backward over the colon, do not force the normal contents back through the valve into the small intestine again. I have seen hundreds of such constrictions, and only twice have there been exceptions to this rule—once under normal conditions, when a small mass slipped back into the ileum; and at another time when a large amount of water had been introduced into the colon.

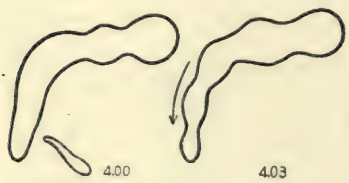

FIG. 28.—TRACINGS SHOWING CHANGES WHEN FOOD ENTERS THE COLON, AND ALSO THE FIRST TONIC CONSTRICTION.

4.00, the colon relaxed as food approaches in the ileum; 4.03, the colon contracted and traversed by antiperistaltic waves after the food has entered.

The X-ray observations on antiperistalsis of the cat's proximal colon which I published in 1902[3] were confirmed in 1904 by Elliott and Barclay-Smith, who studied the activities of the large bowel in the abdomen opened under warm salt solution.[4] They called attention also to a fact which had been overlooked, that Jacobi had reported, in 1890, colonic antiperistalsis in the cat, noticed incidentally during a research on colchicum-poisoning.[5] By the X-ray studies and by the investigations of Elliott and Barclay-Smith, however, the reversed peristaltic movement of the proximal colon was definitely established as a normal activity. These returning waves have now been seen in the dog,[6] in the rat and guinea-pig, and to some extent in the rabbit, hedgehog, and ferret.[7] When a well-developed cæcum exists, there may be an interplay between its peristalsis and the antiperistalsis of the proximal colon, as in the rat; or, as in the rabbit, the cæcum may feed material into the mixing apparatus of the proximal colon. In the herbivores which they studied, Elliott and Barclay-Smith found that sacculation of the proximal colon was associated with churning movements, each sacculus becoming at times the seat of swaying oscillations. The greater the churning activity

of the proximal colon, the more marked was the sacculation of its wall.

The colon of man is of the sacculated herbivorous, rather than of the carnivorous type. As all observations have indicated, the sign of a proximal colon which mixes and churns its contained material is a uniform soft consistency of its contents. Only in the cæcum and ascending colon is this condition realized in man ; the contents of the transverse colon, I have already stated, are generally as firm as those of the rectum. From the nature of the contents, Elliott and Barclay-Smith assumed that in man the material entering the proximal colon " is still delayed by a backward current, still commingled by the activity of the walls of the sacculi."

The support for the view that antiperistalsis occurs in the human proximal colon is at present inferential. In cases of cæcal fistula, rectal enemata will often traverse the entire length of the colon, and escape through the artificial opening. In these cases also, surgeons have endeavoured to stop the fæcal discharge by transplanting the ileum into the transverse colon, and they have found that the discharge still continues. Indeed, one case is reported in which the ileum was sewed into the lower end of the descending colon ; and since the discharge through the fistula in the cæcum persisted, the colon was finally cut across, and closed immediately above the junction in order to stop the backward transportation of material.[8] The larger amount of contents in the proximal colon has also been considered evidence of antiperistalsis. Thus, Roith has found that the cæcum and ascending colon contain on an average about twice the amount of material present in an equal length of transverse colon, and three to five times as much as an equal length of descending colon.[9] This observation, however, might be explained by the capacity of the cæcum being greater than any other part of the large intestine,[10] and by its possessing a very thin wall.[11] Significant X-ray evidence has been brought forward by Stierlin, who has published radiographs showing that the proximal colon holds part of the food containing the bismuth salt after the rest has passed on into the distal colon,[12] and that it retains this material longer than any other part of the alimentary canal. These observations, I may state, are in harmony with the conditions in experimental animals in which antiperistalsis has been demonstrated. Stierlin has also pointed out that the cæcum is the widest part of the

entire intestinal canal, and that in this region the separation of the contents in sacculi or haustra is often absent or only slightly developed.[13]

Although the escape through cæcal fistulas of material introduced distally in the colon clearly demonstrates a backward current in the human large intestine, and although the great volume of cæcal contents and their long retention are indicative of antiperistalsis, the phenomenon has not yet been seen in man. Hertz has testified to having watched with the X rays the shadow of the human colon for various periods in a large number of individuals, without seeing antiperistalsis. Even when an enema containing bismuth was introduced under pressure until the whole colon was visible, he saw no sign of antiperistaltic activity.[14] Much weight should not be given, however, to this negative evidence, for in all animals in which antiperistalsis of the colon has been seen, its occurrence has been occasional. In observations on these animals, I have had experiences that almost parallel those of Hertz on man. Even in experimental conditions most annoying failure to evoke antiperistalsis was common in my experience until the great significance of the tonus ring as a source of the waves was realized—a relation to be considered later. Possibly when tonic contractions can be produced in the human colon antiperistaltic waves will be revealed.

Since the circular coat of the ileum is thickened at the junction with the colon, Keith[15] suggested, in 1903, that in most animals, probably including man, not merely a mechanical valve, but a true sphincter, separates the large and small intestines. The next year Elliott proved physiologically the existence of such a sphincter in the dog, by showing that it was subject to special nervous control different from that of neighbouring parts of the intestinal tract.[16]

Antiperistalsis in the colon gives new meaning and value to the location of a sphincter or valve at the opening of the ileum. For, inasmuch as the valve is normally competent, the constrictions repeatedly coursing toward it force the food before them into a blind sac. The effect on the contents must be the same as the effect seen in the stomach when the pylorus remains closed before the advancing waves. The confined material is pressed upon by the approach of each constriction ; but since it cannot go onward in the blind sac, and is, moreover, subjected to increasing pressure as the constriction comes nearer, it is forced into the

only way of escape—*i.e.*, away from the cæcum through the advancing constricted ring. About twenty-five waves in the cat affect thus every particle of food in the colon during each normal period of antiperistalsis. The result must be again a thorough mixing of the contents, and a bringing of these contents into close contact with the absorbing wall—a process which has already been variously repeated many times in the stomach and in the small intestine. The last remnants of value in the food, with some of the water, are here removed; and the waste is passed onward into the distal colon to be ejected from the body.

In 1894, Grützner[17] published an observation and made an assumption about which there has since been much controversy. He stated that when normal salt solution, holding in suspension hair, powdered charcoal, or starch grains, is injected into the rectum, it is carried upward into the small intestine, and may even enter the stomach. These experiments have been repeated by several observers. Some have confirmed Grützner's results; others have failed, after using most careful methods, to find any evidence of the passage of the injected material back to the stomach, and they have declared that the apparent success was due to carelessly allowing the food of the animal to become contaminated with the test materials, so that these were introduced into the stomach by way of the mouth.

By means of the X rays it is possible to see just what takes place when a fluid is injected into the rectum. For the purpose of determining how nutrient enemata are received and acted upon in the intestines, I introduced in large and small amounts thin fluid masses and thick mushy masses, in different animals. The enemata consisted of 100 c.c. of milk, one egg, 10 to 15 grammes of bismuth subnitrate, and 2 grammes of starch, to hold the bismuth powder in suspension. To make the thick enema, all these were stirred together and boiled to a soft mush; to make the thin enema, all the parts were boiled together except the egg, which was added after the boiled portion was cooled. The small amount injected was 25 c.c.; the large amount almost 90 c.c., about the capacity of the large intestine when removed from the body. The animals were given first a cleansing injection, and after this was effective the nutrient material was introduced. In order to make sure of the observation, a control radiograph was first taken to show no bismuth food present, and other

radiographs were taken at varying intervals after the injection to record the course the food was following.

When small amounts of nutrient fluid were introduced, they lay first in the distal colon. In every instance antiperistaltic waves were set going by the injection, and the material was thereby carried to the cæcum. When large amounts were injected, they stopped for a moment in the region between the second and last third of the colon, as if a constriction existed there. Then a considerable amount of the fluid passed the point, and the antiperistaltic waves began their action. In any case the repeated passing of the waves seemed to have the effect of promoting absorption, for in the region where they continued running the shadows became gradually more dim, and finally the bismuth appeared to be only on the intestinal walls ; in other regions—*e.g.*, in the distal colon—the shadows retained their original intensity. Small injections were never, in my experience, forced even partially into the small intestine ; but with the larger amounts, whether fluid or mushy, the radiographs showed many coils of the small gut filled with the bismuth food.

The pressure required to force the injected material beyond the ileo-colic sphincter is probably due largely to antiperistalsis in the colon—a factor unknown to both Grützner and his opponents. The sphincter which is thoroughly competent for food coming normally from the small intestine into the large is, for some unknown reason, incompetent for a substance, even of the consistency of thick cream, introduced in large amount by rectum. When the valve first permits the food to enter the ileum, the fluid pours through, and appears suddenly as a winding mass occupying several loops of the intestine. The winding mass is continuous from the valve to the other end ; antiperistalsis is therefore not visible in the small intestine under the circumstances of this experiment. The antiperistaltic waves of the colon, however, continue running ; the proximal colon is thus almost emptied, and the small intestine more and more filled with food. After a short time the typical segmenting movements can be seen in the loops, busily separating the food into small masses and over and over again dividing and redividing them.

I have never seen injected material passed back from the colon as far as the stomach ; but once, about ten minutes after an injection of 100 c.c. of warm water, the cat retched and vomited

a clear fluid, resembling mixed water and mucus. In the fluid were two worms, still alive, commonly found in the intestine.

As material accumulates in the proximal colon, we have learned that it is at first confined there by antiperistaltic waves. With further accessions, however, the contents naturally must be pressed more and more into the distal colon. In the early stages of this accumulation, while the food lies chiefly in the proximal part, the only activity of the muscular walls is the antiperistalsis. As the contents extend along the intestine, a deep constriction appears near the advancing end, and nearly separates a globular mass from the main body of the accumulation. The contents of the large intestine progress farther and farther from the cæcum; meanwhile new tonic constrictions appear, which separate the contents into a series of globular masses, which are present chiefly in the distal colon (Fig. 27). Similar appearances are observable in the terminal portion of the rabbit's colon, in which deep circular constrictions separate the scybalous masses, and push them onward by regular peristalsis. Comparing tracings made at rather long intervals (forty-five minutes), I found that as the colonic contents increased the rings disappeared from the transverse colon, and were then present with the waste material in the descending colon. Thus in the cat also these rings, which seem with short observation to be remaining in one position, are probably moving slowly away from the cæcum, pushing the hardening contents before them. The contents at this stage are no longer fluid, and consequently they must offer considerable resistance to a force pushing them towards the rectum. It is an advantage to have this pultaceous material propelled in divisions rather than in a uniformly cylindrical mass, since the fibres along the length of the mass are thereby rendered effective. Such seem to be the functions of the persistent rings: to form the waste matter into globular masses at the end of the proximal colon, and to push these masses slowly onward.

The rate of progress of material through the large intestine in man has been studied by Hertz with the X rays. He states that the time required for each part of the colon—ascending, transverse, and descending—is about two hours. That is, about the same period is occupied in passing through the 2 feet of colon between the cæcum and the splenic flexure as through the $22\frac{1}{2}$ feet of small intestine.[18] The movements of the human colon, however, appear to be less active at night than during the

day. In one individual, for example, a bismuth content was present at the end of the descending colon eight hours after being ingested at breakfast; but when taken at 10.30 p.m. it had reached only the end of the ascending colon after twelve hours. The taking of meals also is stimulating to the colon; by making tracings hourly after a bismuth breakfast, Hertz found that, apart from meals, progress through the colon was slow, but that after each meal there was perceptible advancement of the contents. More progress occurred, for example, during the dinner-hour than during the previous four hours.[19]

According to Holzknecht,[20] who in two cases was fortunate in seeing the activities of the human colon by means of a fluorescent screen, the contents of one section are moved onward into an empty distal section by a sudden push, lasting only a few seconds. The haustral segmentation disappeared just before the advance began, but reappeared at once when the material became settled in the new position. Holzknecht has suggested that by three or four such pushes, lasting about three seconds, the whole colon would be traversed. The functions of the haustra, under these circumstances, would probably be concerned with increasing surfaces for absorption, and not with propulsion of their contents.

The process of clearing the colon is in the cat a process of gradual reduction of the material present. The first radiograph in Fig. 29 shows the appearance of material in the colon at 3.11 p.m. Later, with a slow, sweeping movement, the gut swung around to the position shown in Fig. 29, 3.25. At the same time the tonic constrictions disappeared, much as the haustral indentations disappear in man, and were replaced by a strong, broad contraction of the circular muscle, tapering, the contents off on either side in two cones. The region of strongest contraction was apparently drawn downward with the rest of the gut by a shortening of the descending colon. As the intestine swung around, more material was forced into the rectum; and when the swinging of the intestine stopped, the constriction which divided the lumen passed slowly downward, and with the aid of the muscles surrounding the abdominal cavity pushed the separated mass out of the canal. After the terminal mass had thus been pushed out, the colon, with the remainder of its contents, returned to nearly its former position (Fig. 29, 3.46). About two hours afterward this remnant had been spread throughout the length of the large intestine by means of the

3.11

3.25

3.46

FIG. 29.—TWO RADIOGRAPHS AND A TRACING SHOWING THE CHANGES TAKING PLACE IN DEFÆCATION.

3.11, material in the colon; 3.25, colon carried downward and terminal mass separated; 3.46, after defæcation, when the colon had returned to former position. Defæcation occurred at 3.27.

slowly moving rings. Fig. 27 is a radiograph of the same colon pictured in Fig. 29 ; the radiograph was taken at 11.50 a.m., and at 12.15 p.m. the material in the distal colon was forced out in the manner above described. Within three hours the remaining portion had been spread into the evacuated region, as shown in Fig. 29, 3.11.

The manner in which the material is spread from the region of the antiperistaltic waves into the region of the tonic constrictions presents a problem. During normal living new food constantly arriving in the colon must force the old contents forward, just as the later parts of a meal force forward the earlier parts ; there is no doubt, however, that most of the contents of the proximal colon may be passed onward even during starvation. The emptying of this region, according to my observations, is never complete ; for after considerable time has elapsed, and the large intestine is cleared and dilated with gas, some substance is still to be detected in the cæcum and clinging to the walls of the ascending colon, an observation which Hertz has recorded also for human beings.[21] The only activities manifested here are the antiperistaltic waves, and the strong tonic contraction of the whole circular musculature shown in Fig. 28. It is clear that the latter activity would serve to press into the transverse colon a considerable portion of the contents of the ascending colon, and the remnant seen clinging to the walls would be the part not thus pressed forward.

Twice I have seen appearances which might account for the emptying of the first portion of the large intestine in a more thorough manner than that above described. At one time, without apparent stimulation, a strong tonic contraction occurred along the proximal colon, which almost wholly forced out the contents. This action seemed merely an exaggerated form of the contraction observable after food passes the ileo-colic valve. At another time, after a mass of food had passed through the ileo-colic valve, after the proximal colon had contracted generally, and the antiperistaltic waves had coursed over it in the usual manner, a deep constriction appeared at the valve and ran upward without relaxation nearly the length of the ascending colon, pushing the contents before it. For an instant the wave paused ; then the constriction relaxed, and the food returned toward the cæcum. These observations indicate that either a general contraction of the wall of the large intestine or a true

peristalsis may be effective in pressing waste matter from the region where antiperistalsis is the usual activity into the region where it may be carried on to evacuation.

The function of the colon during defæcation has also been observed in the cat by Elliott and Barclay-Smith,[22] who found complete agreement with the account given above. In man the changes have been studied and described by Hertz, who used the X-ray method.[23] As in the cat, a relatively long column of fæces is passed out at one time; Hertz's tracings show that the entire large intestine below the splenic flexure is normally evacuated at a single act. Thereafter, usually during the next twenty-four hours, waste material accumulates in the distal colon. It first stops at the junction between the pelvic colon and the rectum, where an acute angle offers some obstruction to progress. Then from below upwards the pelvic colon fills, and, if more material arrives, it gathers progressively in the iliac and descending colon. On becoming distended the pelvic colon rises, and widens its acute angle with the rectum, thus removing the obstruction to advancement of fæcal matter. Some of this matter now entering the rectum leads to the desire to defæcate. The common performance of the act regularly after breakfast is probably due, in part at least, to stimulation of peristalsis in the colon by taking food, aided by the muscular activities that attend arising and dressing. When these procedures do not result in the natural "desire to defæcate," voluntary contraction of the muscles surrounding the abdominal cavity may cause some fæces to enter the rectum, and thus evoke the call.

When the call to defæcation has come, the further performance of the act is accomplished primarily by increased intra-abdominal pressure—a result of voluntary contraction of the abdominal muscles and the diaphragm. As the diaphragm contracts, the entire transverse colon is pushed downward, and the ascending colon and cæcum are forced into an almost globular form. The intra-abdominal pressure, as measured in the rectum during this stage, may be from four to eight times the normal—*i.e.*, may be between 100 and 200 millimetres of mercury.[24] The pressure causes more fæces to enter and distend the rectum and the anal canal. The distension of these parts now arouses reflexes which start strong peristaltic contractions of the colon, continues the tendency to strain with the voluntary muscles, and produces relaxation of both anal sphincters. Although, as here described,

the process involves voluntary factors, it is quite capable of being performed perfectly by the spinal animal.[25]

The material below the splenic flexure is in most cases thus normally voided, and at the same time, according to Hertz's tracings, much of the content of the ascending colon and cæcum is pushed onward into the transverse colon. The sort of peristaltic activity of the colon that Holzknect has observed occurs, therefore, at the time of defæcation, and results in an advancement of the fæcal contents in at least two large divisions. If approximately nine hours are required for material to reach the descending colon in man, the waste from food taken at eight o'clock in the morning might be discharged at five o'clock in the afternoon. If defæcation should occur regularly at four o'clock, however, the waste from breakfast must be retained for another twenty-four hours. Thus, as Hertz has pointed out, the interval between a meal and the excretion of its residue will vary, when the bowels are opened regularly once a day, between nine and thirty-two hours, the period depending on the time of eating and the time of defæcation.

The importance of responding as soon as the desire to defæcate arises is shown by the observation that the rectum accommodates itself to the presence of a fæcal accumulation,[26] and then does not produce the desire. If the signal is not soon obeyed it ceases to be given; the fæces may then remain long in the rectum without calling forth sensations, and the defæcation reflex be to that extent impaired. As material emerges, therefore, from the control of automatisms that have governed its passage through the digestive canal, and enters the region where voluntary interference is again possible, disturbances are likely to arise because the automatic call for exit can be voluntarily suppressed.

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CHAPTER XIII

AUSCULTATION OF GASTRO-INTESTINAL SOUNDS

In reporting, in 1902, observations on the movements of the intestines, I made note[1] of an instance of rhythmic sounds accompanying the rhythmic movements in the small gut. It occurred to me at that time that the sounds heard over the abdomen might indicate the mechanical activities going on in the alimentary canal in man, but it was not until a few years later that my attention was strongly aroused to the interest and possible practical value of abdominal auscultation.[2] The loud gurgling sounds produced by the intestines were, of course, observed and recorded centuries ago ; the descriptive designation " borborygmus " was employed even by Hippocrates. And Robert Hooke, in a remarkable passage written more than a hundred years before Laennec, suggested "that it may be possible to discover the Motions of the Internal Parts of Bodies . . . by the sound they make, that one may discover the works performed in the several Offices and Shops of a Man's Body, and thereby discover what Instrument or Engine is out of order, what Works are going on at several Times and lie still at others " ; and in support of this idea Hooke mentioned, among other instances, the hearing of the " Motion of Wind to and fro in the Guts."[3] The suggestion that abdominal sounds may be useful in discovering the works of the stomach and intestines has, however, received but scant attention. In 1849, Hooker published an essay,[4] in which he described variations in the frequency and intensity of intestinal gurglings in the course of different diseases of the digestive organs. Since that time other writers have classified the sounds normally audible into splashings, rattling or rustling noises, the transmitted murmurs of respiration, and the rhythmic pulsation of the aorta.[5] These sounds, however, according to L. Bernard,[6] are not constant over the abdominal

organs nor do the vibrations heard characteristically in the healthy individual alter in pathological conditions. Even in the most recent and most complete treatises on auscultation, the only additional statements, so far as the gastro-enteric tract is concerned, are with regard to the rubbing noises audible in cases of inflammation, and the piping notes that can be heard when there is intestinal stenosis. Any further notice of the facts or possibilities of auscultation of the stomach and intestines during digestion I have been unable to find.

As anyone can easily determine, the abdomen is not poor in noises ; on the contrary, it is usually much richer than the thorax, and the noises are of the most diverse character, from soft gurglings to loud rumbling explosions. Any special attention to the peculiarities of certain sounds in the general tumult audible at the height of digestion was hardly to be expected, so long as the nature of the motor activities of the stomach and intestines was not well understood. The recent increase of our knowledge of these activities, however, enables us to recognize more accurately the relation between the movements of the alimentary canal and the sounds these movements produce.

The most characteristic feature of the movements of the stomach and intestines is without doubt rhythmicity. Peristaltic waves pass in rhythmic succession over the gastric vestibule, rhythmic segmentation kneads the contents of the small intestine, and antiperistaltic waves rhythmically follow one another in the proximal colon.

The condition most favourable for the production of sounds in the alimentary canal is the presence of a gas mixed with food more or less fluid. When the food and the gas are churned together, a sound must result. Air in fine division can be introduced into the stomach by eating in combination with other food, or by themselves, such preparations as soufflés, light omelettes, toast, or very porous bread. I have also used a thin paste of gluten-flour and milk, thoroughly stirred with white of egg until the mixture was frothy. Eaten with a little cream and sugar, this mixture is not unpleasant. These preparations should not be chewed so thoroughly as to drive much of the air from the small cells in which it lies enclosed. When such food is eaten, rhythmic sounds can be heard over the pyloric end of the stomach, and later over the lower quadrants of the abdomen.

In listening to these sounds I have made use of a flat-disc

stethoscope, with the metal chamber 2 inches in diameter. The flatness and weight of the metal chamber render it so stable that it remains where placed without being held, and by the addition of a rubber tube of sufficient length the stethoscope will reach easily to any situation on the observer's own abdomen. For several months I kept the stethoscope at hand near my bed, and when not asleep used it in listening to the sounds of digestion. At times, in the quiet of the night, it is possible to hear the sounds without the stethoscope. Indeed, the vibrations are sometimes so strong that they can be felt in the abdomen, or perceived like the tactile fremitus of the chest, by placing the hand over the region in which the sound arises.

The rhythmic sounds are not due to respiration; they differ from the respiratory murmurs in rate and time. Nor are they due, as one who hears the confusion for the first time might suspect, to the chance choice of a rate and the selection of such sounds out of the confusion as correspond to that rate. Graphic records of the sounds produced by the stomach and small intestine have been secured, and the element of human judgment thereby eliminated. In registering the sounds of digestion I have employed the first method used by Hürthle[7] to register the heart-sounds. A telephone transmitter, rendered specially sensitive by the use of rather coarse carbon granules loosely disposed, was connected in series with five dry cells (total electro-motive force 5·5 volts) to the primary coil of an inductorium. The secondary coil of the inductorium was attached to platinum electrodes in a moist chamber. Over the electrodes lay the nerve of a nerve-muscle preparation. The contraction of the muscle raised a lever which wrote on a smoked drum. So sensitive was this arrangement that ordinary conversation could not be carried on near the apparatus without marring the record. Sound vibrations seem to be conducted from one point to another in the abdomen much better than in the thorax. But when sounds not arising immediately under the transmitter caused the muscle to contract, the recording of these muffled outlying vibrations could be largely avoided by withdrawing the secondary coil of the inductorium to a proper distance. In order that the observer might listen to the sounds while they were being recorded, a telephone receiver was arranged to be thrown into circuit at will.

The Sounds produced by the Stomach.—The active end of the stomach is the pyloric end. The food in the vestibule, as we

have already seen, is repeatedly compressed by peristaltic waves moving up to the pylorus. If the sphincter does not relax as the ring of constriction approaches, the only escape for the food is back through the narrow advancing ring (*cf.* Fig. 4). Since the waves are recurring with rhythmic regularity and the pylorus relaxes only occasionally, the food near the pylorus must be squeezed and regurgitated by wellnigh every constriction ring.

That the rhythmic gastric sound is caused by the escape of the food backward through the narrow moving orifice was proved by the following observation. A mixture of starch paste, white of egg, and subnitrate of bismuth, stirred with an egg-beater until frothy, was given by stomach-tube to a cat. The cat's hair had been cut short over the pyloric region, and the skin wet with water. When a stethoscope was applied, little gurgling explosions could be heard at intervals of about thirteen seconds. The animal was then examined with the X rays, and peristaltic waves were found recurring at intervals of thirteen or fourteen seconds. As a constriction was about to pass up to the pylorus, the noisy X-ray machine was stopped, and the stethoscope applied. At the proper time the characteristic sound occurred. Meanwhile no food had left the stomach; the sounds must have been due to the regurgitation of the food through the advancing peristaltic ring.

Since the pyloric end of the stomach reaches farther to the right than any other part, it is clear that by reclining on the left side the pyloric end will be brought uppermost. When the stomach is so situated, the lighter food—*i.e.*, food mixed with air—will naturally rise into the pyloric end. Peristaltic waves passing over this somewhat viscous mixture of air and chymous food will then, for reasons already stated, produce audible vibrations. Sounds quite distinct when a subject lay on his left side became very weak or inaudible when he turned so that the pyloric end was lowermost.

The stomach-sounds can best be heard after a fairly bountiful meal in which has been included a large admixture of the food of spongy consistency already mentioned. The subject should lie on his left side. The disc of the stethoscope should be placed about midway between the umbilicus and the lower end of the sternum, and to the right of the median line. Not all persons I have examined have exhibited the sounds. When the sounds appear, however, they are usually loud, rattling, explosive, and

of a characteristic quality quickly recognized after they have once been fixed in mind. But occasionally there is only the recurrence of a short series of pops. In some individuals the sounds are louder and more distinct than they are in others ; and in all the cases I have studied, the sounds, even within two or three minutes, have varied considerably in intensity. At times the characteristic explosive discharges last several seconds ; at other times there is at the regular period merely a sharp, short report. Between the moments when the typical sounds return, one can ordinarily hear with more or less distinctness a sudden little pop, and perhaps several, always coming at irregular intervals. These sharp pops, which resemble the bursting of bubbles, can be heard in all parts of the abdomen, but with greatest frequency on the right side.

The gastric sound recurs approximately every twenty seconds. In one individual the interval was usually from seventeen to nineteen seconds ; in another, about twenty-one seconds ; and in a third, about twenty-four seconds. These rates vary, as the rate of gastric peristalsis in the cat varies (see p. 54), at different times in the same individual. In the first case mentioned above, for example, the interval was occasionally twenty and twenty-one seconds. In all lower animals, except the rabbit, that I have examined with the X rays, peristaltic waves have been found running over the stomach with monotonous regularity whenever, during gastric digestion, the animal has been observed. In man, also, gastric peristalsis probably runs in continuous rhythm until the stomach is empty, for in one case observation during the first four hours after a meal revealed only occasional short interruptions of the rhythmic sounds. The sounds are likely to be thus interrupted even when they have been for some time clearly and regularly audible. The silence may cover one, two, or even three of the regular periods. It is noteworthy that when the sound can be heard again it continues the previous rhythm. This fact is illustrated by the following figures, showing the number of seconds between successive gastric sounds about two hours after dinner :

19	20
38 = 19 + 19	19
18	19
19	20
59 = 19 + 20 + 20	38 = 19 + 19
19	20

The equations show that the normal periods have been preserved; the peristaltic rhythm, therefore, has probably been continuous although each wave has not produced a sound. The sound just previous to a silent interval is likely, in my experience, to be somewhat louder and more prolonged than is usual. This prolonged sound may mean a discharge of food through the pylorus, and thereby the conditions in the vestibule may be so altered that the immediately succeeding waves can cause no sounds until the region is again normally filled; but I have no evidence of this.

Fig. 30 is the copy of a record, secured by the telephone method previously described, which shows graphically many of the features of the stomach-sounds above mentioned. The different heights of the separate marks indicate variations in the intensity of the sounds. The duration of the sounds also can be

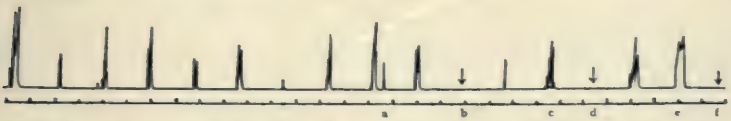

FIG. 30.—GRAPHIC RECORD OF THE STOMACH-SOUNDS SECURED BY PLACING OVER THE PYLORIC REGION A TELEPHONE TRANSMITTER ACTIVATING A NERVE-MUSCLE PREPARATION.

The time is marked in intervals of ten seconds.

judged; for example, at *c* and *e* they are more prolonged than before *a*. One of the intermediate pop sounds is recorded at *a*. Silent intervals are indicated in the regions *b*, *d*, and *f*. In these regions arrows have been placed at the points where the sounds would have recorded if present. The regular rhythm is resumed in continuation of the previous rhythm. The silent intervals are not always so frequent as this record shows them; I have one tracing in which the marks are not only rhythmically regular, but of almost the same height, uninterruptedly for fifteen minutes.

The evidence that the rhythmic sounds audible over the pyloric region are due to the rhythmic recurrence of peristaltic waves moving up to the pylorus has been presented in a comparison of the conditions in man and in the cat. This evidence is confirmed by observations of Moritz on himself. He introduced a stomach-tube into the pyloric end of his stomach, and found that there were rhythmic oscillations of the intragastric pressure in that region. Examination of his records proves that the rate of

gastric peristalsis, in his case also, is approximately three waves per minute, or waves at intervals of about twenty seconds.[8]

Hertz has reported[9] hearing at intervals of eighteen and twenty seconds sounds like those I had described. In one case he states that he heard "a series of short pops repeated with perfect regularity every seventeen seconds for about five minutes." In some instances, however, Hertz was unable to hear any rhythmic sounds arising from the stomach, an observation which accords with my own experience. When the narrowness of the peristaltic ring of the vestibule is considered, however, the securing of reliable auscultatory evidence of gastric movements seems not an impossibility. The conditions for producing vibrations in gastric contents driven through the narrow ring must be more exactly determined.

The Sounds produced by the Small Intestine.—Rhythmic segmentation, although not always present, is by far the most common mechanical process to be observed in the small gut. The segmenting movements have a more rapid rate than the stomach movements. In the cat and the dog rhythmic contractions of the small intestine are from three to five times as frequent as the waves of gastric peristalsis.

Usually, on listening over the lower abdomen, especially over the right lower quadrant, during the height of digestion, the observer hears what seems at first only a great confusion of noises. Without experience it is difficult to distinguish in the midst of this tumult the rhythmic sounds of the small intestine. It is well to listen in the night after the stomach is empty, or, better, an hour or two before breakfast. The stomach is then producing no sounds, and the active part of the large intestine can be avoided by placing the disc of the stethoscope over the lower left quadrant of the abdomen. As already mentioned, these sounds can sometimes be heard in the quiet of the night without the use of the stethoscope. I have heard them thus, and determined their rate by listening at the same time to a clock ticking twice a second.

The rhythmic sound of the small intestine is different in quality from the gushing, explosive sound of the stomach. To be sure, the intestinal sound is not always the same : sometimes it is a soft rustling of fine crepitating noises ; sometimes a group of little rattling explosive discharges, as if an exaggerated crepitation ; and sometimes—as heard through the stethoscope—a rough

rolling rumble, like miniature thunder. But after these variations in quality there remain three features of the intestinal sounds that are fairly distinctive. First, the individual sounds usually rise slowly to an acme of intensity and then gradually subside; but they may increase slowly to a maximum and suddenly cease, or may begin loud and then gently decrease to silence. Thus each sound may last two or three seconds or more. The second characteristic is the persistence of the rhythm for some time in one place; it may be audible for a minute, or it may last for many minutes, but it does not move away as the sound produced by a peristaltic wave would move. The third feature is the distinctive rate. This rate is usually one sound every seven or eight seconds, but I have heard the sounds four or five seconds apart, and at times ten seconds apart. This rate would occasion from seven to twelve movements per minute. The rhythmic contractions of the small intestine are thus from two to four times as frequent as the waves of gastric peristalsis, a ratio corresponding to that in the cat and dog. This fact and the fact that the rhythmic sounds can at times be heard loudest in the left flank, far from the active ascending colon, have led me to regard these sounds as a result of the activity of the small intestine rather than of the colon. Of course, at any one time there will be some variation in the rate, but usually it is not great, as the following figures, showing the number of seconds between the beginnings of successive sounds, will indicate:

8	8
8	15 = 7 + 8
6	9
8	6
13 = 7 + 6	9

As these figures illustrate, the sound sometimes skips the regular period, but continues the rhythm on reappearing.

In the morning, after an ample dinner the evening before, I have heard these rhythmic sounds continue in one part of the abdomen or another without interruption, for more than an hour and a half. The intestinal sounds are not peculiar to the morning hours, though they are most clearly distinguishable at that time. After learning their qualities and rate, I have heard them distinctly in the midst of active digestion in the afternoon and evening. Nor are they peculiar to the left side of the body. At times I have heard them loudest on the right side.

In describing, in 1902, the rhythmic sounds attending rhythmic segmentation in a cat with opened abdomen, I stated: "As new rings occurred the old relaxed, but apparently with tardiness, for the contents gurgled as if forced through the narrowed lumen."[10] The contraction of the circular muscle at fairly regular intervals along the length of a mass of food cuts the mass into segments, and the repeated splitting of these segments to form new segments must bring about with each operation a squeezing and shifting of the food, almost simultaneously along the whole extent. If the food contains air, the squeezing and shifting will result in audible rumblings and crepitations. The presence of valvulæ conniventes conceivably causes the sounds to be louder than they would be in a smooth intestine. The rather long duration of these sounds—sometimes three seconds and more—led me to think that the process in the human body is like that

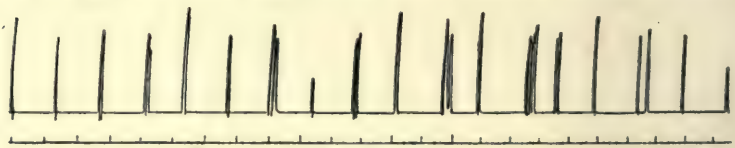

FIG. 31.—GRAPHIC RECORD OF THE RHYTHMIC SOUNDS OF THE SMALL INTESTINE.

The height of the records has been reduced to one-fourth the original size. The time is marked in intervals of five seconds.

observable in the cat and dog, and not the simple to-and-fro oscillation of a small bit of food observable in the rabbit.

These observations, made in 1905, have not yet been confirmed by others. In 1907, Hertz reported his failure to hear rhythmic sounds of the character I had described. He succeeded, however, in observing with the X rays rhythmic segmentation in the human small intestine, and at almost exactly the rate I had noted for the sounds which I attributed to the segmenting movements (see p. 133).

The subjective element in the auscultatory evidence for these sounds is eliminated when they are made to record themselves. Such a record, secured by the method already described, is shown in Fig. 31. It is a record of sounds heard before breakfast one morning about 9.30 o'clock. The dinner at 6 o'clock the previous evening consisted of grape-fruit, mackerel, potato, cucumber and tomato salad, four slices of bread and butter, and strawberries and cream with cocoanut cakes. About 10 o'clock

in the evening four slices of bread and butter and a glass of milk were taken. At the time this record was made the telephone transmitter was placed on the lower left quadrant of the abdomen. The duration of the sounds is not indicated, since the recording muscle contracted in each case only at the climax of intensity.

The Sounds produced by the Large Intestine.—Antiperistaltic waves moving toward the cæcum must press the food into a blind pouch, and the only escape for the food must be, as in the stomach with the pylorus closed, back through the advancing ring. Each peristaltic wave should produce a sound, therefore, similar in quality to that of the stomach. From the analogy of the cat and dog, one would expect these waves to have about the same rate of recurrence as the gastric waves. One would expect, likewise, that they would run, not continuously, like the gastric waves, but for short periods, when new masses of food enter the colon from the small intestine; that they might appear, as in the cat, after the injection of a large enema; and that during the periods of activity the waves would follow one another in a fairly regular rhythm.

The greater activity in the right lower quadrant of the abdomen is manifested by the more frequent occurrence of sounds there than in the left lower quadrant. At times an almost constant succession of little popping noises and faint gurglings can be heard in the region over the ascending colon when the region over the descending colon is quite silent. But in spite of listening in the region of the cæcum for hours, at different times of the day, and with my body in various positions, a uniform and characteristic rhythm of the sounds in this region, if it be present, has escaped me. Sounds of a coarse rumbling character, somewhat like those of the stomach but usually more prolonged, are at times audible. These sounds were once heard recurring regularly for a short period at intervals of about twenty seconds. More commonly, in my experience, such irregular intervals as these—45, 25, 35, 27, 25, 14, and 29 seconds—are observable. Inasmuch as these sounds are not clearly rhythmic, it seems questionable whether they are produced in only one part of the intestine. But these gurglings are heard loudest along the ascending and transverse colon, and for that reason are probably due to activities of the large bowel.

The absence of a regular rhythm in the repeated contractions of the large intestine has been supported by experience with enemata. The enemata consisted of starch and a little flour

boiled in normal salt solution. The resulting paste was thin, yet viscid enough to be stirred into a froth much like soapsuds. Enemata of this kind, made frothy, were introduced at body temperature in amounts varying between 1,500 c.c. and 2,000 c.c. In order to avoid confusing noises from the stomach, their effects were studied in the morning before breakfasting, and they were usually preceded by a cleansing enema of warm normal salt solution. If the body is kept in a horizontal position, the fluid can be retained for a half-hour or more without difficulty. During this time, especially if the pelvis is raised, there are repeated pains or cramps, referred most commonly to the region of the hepatic flexure of the colon. Sometimes the pains are referred also to midway in the transverse, and less often to the ascending colon. They are very distinct and quite unmistakable in their character. It is remarkable that these recurring cramps, which are undoubtedly due to contractions of the intestine, are ordinarily not felt in the descending colon, sigmoid flexure, or rectum, but are restricted to the proximal colon, the region which, in the lower animals, is characterized by the greatest activity.

The contractions attending the pains are not expulsive, nor do they seem to move backward from the part in which they are felt, for no sound is audible over the cæcum either during the pain in the hepatic flexure or after it has disappeared. The contractions apparently occur again and again in the same region without moving in either direction. In the cat I have observed such repeated circular contractions of the proximal colon (see p. 151), but they are not usual.

The recurrent pains ordinarily last from six to eight seconds, increasing gradually in intensity until just before the end. They are commonly attended by gurgling noises audible as the cramp is passing away. The cramps have been observed succeeding one another for nearly ten minutes at intervals varying between nineteen and twenty-two seconds, but in my experience they are ordinarily not so regular as this. The following figures, representing in seconds the time between the onset of successive cramps, illustrate the usual rather irregular recurrence of the contractions :

28	39	22	43
47	35	15	42
35	15	25	40
32	15	50	43
23	18	40	54
41	35	25	37

From the evidence I have been able to secure by auscultation and from sensations of cramp, it seems certain that the ascending and first part of the transverse colon are more active than the remainder of the large intestine. As we have learned, the evidence for antiperistalsis in this more active region is not conclusive. I have already mentioned that Elliott and Barclay-Smith found such sacculation as occurs in the human colon associated with emphasized churning activity of the walls of the sacculi. In repeating their observations on the guinea-pig and rabbit, I have seen oscillating movements of single sacculi, now here, now there, or of many sacculi at the same time, each contracting repeatedly, squeezing out the contents of the pouch, crowding full the neighbouring pouches which in turn became active, then relaxing, filling, and discharging, again and again, till the food was thoroughly churned. Such a process could not be attended by a clearly marked rhythm : too many little activities are going on at the same time. But these little activities would naturally be attended by the continuous popping noises and the slight gurglings which are heard at times over the ascending colon. Is it not likely that in man, even though antiperistalsis may occur in the proximal colon, oscillating contractions of the sacculi constitute the more prominent operation ?

Although auscultation has failed to bring evidence of antiperistalsis in the colon, the method, as used by Hertz, has served to indicate when material begins to pass through the ileo-colic valve. In the morning before breakfast he heard nothing over the cæcum. The silence persisted until between four and four and a half hours after breakfast, when a few quite characteristic sounds were heard, which became louder and more frequent up to a maximum from one to two and a half hours after they began. Then confusions of sounds occurred because of the taking of other meals. The first cæcal sounds were found by the X-ray method to coincide with the first appearance of a shadow in the cæcum. They seemed to be produced by the passage of fluid contents through the ileo-colic sphincter. The presence of gas in the colon was favourable to the production of the sounds, for they decreased in intensity as the semi-fluid material accumulated. In auscultation, therefore, we have a means of determining the rate of passage of material through the small intestine.[11]

A characteristic sound, not periodic, which is audible at times along the transverse and descending colon is a progression of little

crackling noises, like the breaking of minute bubbles. The sound starts in the transverse colon, and its advance can be clearly traced. If the disc of the stethoscope lies over the splenic flexure, the crackling can be heard first faintly, then louder and louder, then gradually more faintly again; and if after the climax of intensity there the stethoscope is changed to a position farther along the large intestine, the sound can again be heard passing through the same phases as before. This sound is likely to be followed immediately by a tendency to pass gas from the bowel. The conveyance of gas from the region of active fermentation in the proximal colon to a place from which it can be finally voided is apparently, therefore, a special action, and conceivably may occur without changing the position of the firm contents of the bowel.

To one listening for the first time for rhythmic abdominal sounds, probably the most striking feature of what he hears is the large number of sounds which are not rhythmic. Most prominent among these irregular sounds are the sudden quick discharges or pops, which can be heard, either singly or in a short series of three or four, almost at all times and in all parts of the abdomen, though most frequently on the right side. As already stated, these reports resemble the sound of bursting bubbles. Occasionally a continuous little gurgling can be heard for some moments, gradually becoming less intense. Peristalsis in the small intestine may be thus manifested.

A noteworthy characteristic of the intestinal sounds is their alteration in intensity and frequency at different times. I have no records showing this variation, but it has impressed itself upon me while listening for long periods to the activities of the intestines. At times there will be almost silence in the lower abdomen; the silence will give way gradually to an abundance of sounds, and these in turn will subside till again only occasional sounds are audible. The observations of Boldireff have proved that the alimentary canal has a periodic activity while not digesting;[12] the intestines may also have alternating periods of increased and decreased activity while digestion is going on.

Whether the observation of the sounds of the stomach and intestines is to be of clinical importance will depend on whether there are typical variations of these sounds in different diseases of the alimentary canal. The observations here recorded, made chiefly upon myself, were confirmed on a few other normal

individuals. No attempt was made to study the sounds produced in abnormal conditions. Irritation in the region of the ileo-colic junction might cause reflex spasm of the sphincter at the end of the small intestine. Material would then cease to pass into the colon, and cæcal sounds would fail to appear. Hertz has suggested that the presence or absence of these sounds would be serviceable in differentiating acute appendicitis with and without peritonitis. In cases of peritonitis of the region, he found that the sounds disappeared as the inflammation developed.[13] Auscultation might also be used to separate the somewhat vague expression "motor insufficiency" into its two factors, absence of peristalsis and pyloric obstruction. Evidently if sounds recur in regular rhythm at the pylorus, and food remains in the stomach, the so-called "motor insufficiency" is due, not to absence of peristalsis, but to difficulty at the pylorus. Furthermore, in such disorders as gastritis, nervous dyspepsia, atony, colic, obstruction, and dysentery, a study of the sounds produced by the movements of the alimentary canal, both before and after the administration of drugs, may reveal facts important to the clinician.

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CHAPTER XIV

THE INTRINSIC INNERVATION OF THE GASTRO-INTESTINAL TRACT

THE relative parts played by the intrinsic and extrinsic nerve-supply of the gastro-intestinal tract can perhaps best be understood by considering first the activities of the canal separated from the central nervous system, and later attending to the modifications of these activities through external connections. The neuromuscular mechanism which underlies peristalsis has been studied chiefly in the small intestine. As we shall see, probably no fundamental difference exists between the intrinsic mechanism in the small intestine and that elsewhere in the alimentary canal. The peculiarities of the activity in different parts of the canal, however, make desirable a separate consideration of each part. Thereafter we shall be in a position to determine to what extent a general statement regarding the entire canal is justified.

The Small Intestine.—Nothnagel pointed out in 1882 that stimulation of the rabbit's small intestine with a crystal of sodium chloride results in a contraction which spreads from the stimulated region upward, whereas complete rest prevails below.[1] After persisting for a variable number of seconds, the contracted region relaxes, and becomes at once the seat of peristalsis. That contraction occurs above, and not below the stimulated region was proved also by Lüderitz, who used a somewhat more natural method—the introduction of an inflatable balloon—and found that rapid distension of the rabbit's gut caused an almost exact repetition of the phenomenon described by Nothnagel. When the intestine was very irritable, the balloon was driven downward by the contraction above it, and thus, by successively stimulating new regions, it caused a downward-moving peristaltic wave. Since these results occurred after the nerves in the mesentery were cut, Lüderitz concluded that the controlling mechanism

must be present in the intestinal wall.[2] The modern conception of intestinal peristalsis was, however, not fully stated until Mall pointed out the significance of Nothnagel's observation on intussusception. Nothnagel had reported that the *intussuscipiens* portion of the gut, lying below the point of stimulation, folds back, and extends upward over the contracted *intussusceptum* lying above.[3] Thus contraction above and relaxation below seemed so related as to be parts of a single act. And Mall concluded that while a mass in the intestine is causing a contraction above, which forces the mass downward and thus stimulates fresh regions above to contract, active dilatation below is at the same time inviting an easy descent.[4] Peristalsis would thus be another example of the mutual adjustment of antagonistic muscles towards efficient action—an example which presents in the simple neuromusculature of the gut the important principles long ago perceived by Descartes and Bell in the neuromusculature of the skeleton, which in recent years have been named by Meltzer and by Sherrington, respectively, " contrary " and " reciprocal " innervation.

Although Nothnagel and Lüderitz had shown experimentally the intrinsic control of peristalsis, and Mall had clearly inferred the nature of the peristaltic wave, Bayliss and Starling made the first exact demonstration of the process. When they introduced a bolus into the dog's intestine, they observed the formation of a " strong tonic contraction " immediately above the object, which pressed it downward. And as the bolus moved, the ring of constriction followed it. The region of the gut over which the constriction ring had just passed was occupied by peristaltic waves, which repeatedly swept down to the ring. By means of apparatus which registered the movements of both the longitudinal and the circular coats, Bayliss and Starling proved that the descending bolus was preceded by an area of relaxation. The two effects, contraction and inhibition, could be produced by pinching the gut above and below the recording apparatus ; a pinch 1 or 2 centimetres below caused the registering of an increased contraction ; a pinch much farther above—even 30 centimetres or more—resulted in cessation of contraction or relaxation. These results appeared after exclusion of cerebrospinal reflexes. " Excitation at any point of the gut excites contraction above, inhibition below. This is the law of the intestine." Such was the conclusion of Bayliss and Starling.[5] Since this co-ordinated action

could not conceivably be performed by muscles alone, they inferred that it was controlled by Auerbach's plexus, possibly by short augmentor paths extending upwards, and long inhibitory paths reaching downwards.

After injecting nicotine, Bayliss and Starling found that rhythmic contractions of a stretched ring of gut continued, but that the waves of constriction, which ran over the gut, now passed as often in one direction as in the other.[6] A pinch caused a local contraction which was not propagated in either direction ; a bolus placed anywhere in the gut remained unmoved. The same results followed painting the intestine with cocaine, or injecting muscarine. They concluded that the rhythmic movements were myogenic, but capable of travelling as a wave from muscle fibre to muscle fibre. Usually these waves moved in a downward direction, an effect which they suggested might result from higher excitability at the duodenal end. True peristalsis they regarded as not like these waves, but as a co-ordinated reflex, consisting of combined contraction and relaxation, dependent on the proper functioning of the local nervous system.[7]

More detailed work on the functions of the local nervous system of the intestine was done by Magnus, and has been reported in a series of valuable papers.[8] Using O. Cohnheim's method,[9] he studied excised pieces of cat's intestine, kept alive in oxygenated, warm Ringer's solution. Thus, Magnus was able to secure records of contraction above and relaxation below the stimulated point in isolated loops. The reflex persisted after removal of the mucous and submucous layers, including Meissner's plexus. It is therefore mediated through Auerbach's plexus—a conclusion which has been inferred by Bayliss and Starling.

Bayliss and Starling's evidence that the rhythmic contractions of the gut are myogenic is not conclusive. That the short augmentor paths and the long inhibitory paths assumed by these investigators are in fact superintending fibres in the wall of the canal, normally affecting subordinate nervous activities in a positive or negative manner, is easily conceivable. Indeed, Dogiel has found histologically that an axon, on leaving a ganglion, frequently passes through several neighbouring or more remote ganglia, and gives off collaterals to the nerve cells lying in them.[10] Nicotine might, then, block conduction between superintending and subordinate neurons, and still leave unaffected the subordinate neurons.

Experimental evidence against Bayliss and Starling's conclusion that the rhythmic movements are myogenic was brought forward by Magnus. His first argument against their contention was based on the distinction between the local motor centres for muscular action and the conducting paths uniting these centres. He had found in the marine worm, Sipunculus, that atropin paralyzes conducting paths, but not the centres, whereas cocaine paralyzes the motor centres before stopping conduction.[11] It was possible, therefore, that the drugs used by Bayliss and Starling, although destructive to the machinery of the local reflex, did not seriously injure the immediate nerve-supply. The rhythmic contractions therefore might result from rhythmic nervous discharges.

The second argument of Magnus was supported by more direct proof. He found that when the longitudinal and circular muscular layers are pulled apart, Auerbach's plexus, which lies between, adheres to the longitudinal layer. Under these circumstances the longitudinal muscle alone manifests spontaneous rhythmic contractions. The circular muscle, deprived of the plexus, although capable of responding to a single mechanical stimulus by a single contraction, never shortens rhythmically.

The objection has been raised[12] that the circular muscle must be seriously injured by separation from the longitudinal coat and the nerve net, and is therefore inert. As Magnus has pointed out, however, removal of the submucosa with Meissner's plexus is, in relation to the circular coat, a similar operation, but it causes no alteration of the activities of that coat ; and, furthermore, the longitudinal coat, which is about one-seventh as thick as the circular, and consequently much more liable to injury, is precisely the part that shows the peculiar rhythmic contractions.[13] This contention of Magnus has been supported by Sick, who succeeded in separating from the stomach pieces of longitudinal muscle without the nerve plexus, and in observing that they then no longer contracted spontaneously.[14]

According to Magnus's careful observations, there are other important differences between intestinal muscle when controlled by the plexus and the same muscle when freed from that control. The independent muscle can be tetanized ; it gives superposed contractions, has no refractory period, and manifests no rhythmic response to continued stimulation. On the other hand, good

preparations with the plexus attached cannot be tetanized, are clearly refractory to weak stimulation during the period of shortening and the first part of the period of relaxation, and with continued stimulation exhibit rhythmic contractions.

Of these activities of smooth muscle connected with its intrinsic nervous system, the most significant, in relation to bodily functions, is the refractory period. Given the refractory period, the rhythmic response to continued stimulation necessarily follows. The rhythmic nature of many of the activities of the alimentary canal might thus receive explanation. The contention of Schultz,[15] that Magnus's " refractory period " was due to defective methods of stimulation, Magnus has met by repeating the experiments under better conditions, and finding again that weak stimulation does not affect the intestinal neuromusculature while it is contracting, and becomes effective again only gradually as the muscle relaxes.[16] Magnus was able furthermore to show the refractory period by mechanical stimulation ; by this method I also have obtained evidence of the phenomenon, and can therefore confirm Magnus's statement.

The question now arises as to the conditions under which the two typical movements of the small intestine appear. The simplest movement to explain is that which causes segmentation. It is only necessary to attach a writing lever to a narrow ring of the intestine to secure a record of rhythmic contractions. The ring may be only a few millimetres wide ; the rhythmic response therefore is local. It can best be explained as a resultant of the stretching. This mechanical stimulation causes contraction ; as soon as the contraction begins, the ring becomes refractory, and is not again subject to the stimulus until it is relaxing. Thus the constant pull results in a rhythmic response. The extent and force of the contractions are increased within limits by an increased distending force, or, if absent, they may be induced in the same way.[17]

In harmony with the foregoing explanation is Bayliss and Starling's observation that the contractions of the gut, when a distending balloon is introduced, are most marked in the region of greatest tension.[18] In harmony with that explanation also is the observation that, as a mass of food is being pushed along the gut, the back end is likely to be cut off by a constriction ring (see p. 137). The violent segmenting activity in cases of obstruction (see p. 141) also points to distension of the gut as a cause of

rhythmic contractions. Indeed, rhythmic segmentation itself is an excellent example of the response of the gut to stretching, for the contraction occurs each time in the bulging region about midway between two previous contractions. Experimental evidence to the same effect I have secured by seizing the active, exposed intestine between the fingers at two points a few centimetres apart, and placing the enclosed contents under pressure sufficient to distend the gut. The distension was followed by the contraction of a narrow ring of the circular coat; and when the finger pressure was repeated rhythmically, as rapidly as a contracted ring relaxed, a new contraction occurred, not where one had just appeared, but in a fresh region. Now here, now there, the gut responded to the distending contents, a shifting perhaps associated with lessened irritability in the region just recovering from activity. Since these rings of constriction press the mucosa into the midst of the food, the requirement of fresh neuromusculature for contraction results, of course, in the utilization of fresh mucosa for absorption.

Why peristalsis of the small intestine starts and why it stops is not known. Certainly nutriment is not pushed onward continuously from stomach to colon. Even in the active small intestine of the rabbit the food-masses can be seen in different loops lying for some time undisturbed by any movement of the wall. In the less active gut of the cat this stasis of the contents is even more marked. Yet from this quiet state, or even after segmentation has been for some time in process, a peristaltic wave will appear, force the mass forward for a short distance, and then stop. Under experimental conditions mechanical stimulation will cause contraction above and relaxation below. Magnus, for example, after removal of all the mucous lining that normally comes in contact with the food, could still demonstrate the reflex by pinching. But the reflex, and the progression of the reflex along the intestine, are not the same phenomenon. Peristalsis implies an advancing wave, and although food containing cellulose seems to be carried through the gut rapidly because of the mechanical effects induced by it, nevertheless the chemical state of the contents is probably of first importance for the moving contraction. Bayliss and Starling found that cotton coated with soft soap was an efficient stimulus for peristalsis of the small intestine. Nothnagel and others used strong salt solutions to evoke it. I have observed energetic peristalsis after

the injection of soapy enemata, and after introducing into the lumen of the gut a small cylinder of alkaline soap. Meltzer and Auer produced rushing peristalsis by administering drugs in stimulating and depressing combinations; the cathartics are irritants of vegetable origin, or salts only slightly absorbable. Most of these agencies would affect the gut not so much by distension as by chemical stimulation. The observation of Bokai,[19] that products of decomposition—carbon dioxide, marsh-gas, hydrogen peroxide, and skatol—cause powerful movements of both the small and large intestines, and Roger's testimony[20] that peptones and glucose stimulate peristaltic activity, are to the same effect. If we consider, furthermore, the other functions of the small intestine which peristalsis subserves—the functions of further digestion and absorption—then the forwarding of the chyme seems required, not because the chyme is bulky, but rather because fresh regions for digestion and absorption are desirable. In an orderly mechanism, therefore, we might reasonably regard the degree of digestion, or the status of the mucosa, or some relation between these two, as a basis for explaining the peculiarities of intestinal peristalsis.

That some regulatory arrangement for the advancement of material through the small intestine exists is suggested by the fact that the different foodstuffs do not pass through the small intestine with the same speed (see p. 145), and yet when the end of the ileum is reached, practically all of the serviceable stuff is absorbed. The work of London and his associates indicates also that foodstuffs are absorbed at different rates at different parts of the tube—meat most in the upper part, starch and fat most in the lower part[21]—and that in each portion of the tract, in the case of any particular food, a constant percentage amount is absorbed, quite independent of the amount fed.[22] Nutriment when given in small bulk (50 c.c.) was distributed in the small intestine quite as it was when given in large bulk (500 c.c.), so that the entire tract is forced into service.[23] These results can best be explained, I believe, as a response of the canal to the nature and state of the intestinal contents, rather than as a response to mechanical stretching. In this connection the control of the sphincters of the stomach by chemical agencies is perhaps significant. The manner in which the chemical character of the chyme may affect intestinal peristalsis, however, is still quite hypothetical, and the whole ques-

tion will require much more investigation before a decisive answer can be given.

Further discussion of the mechanisms governing segmentation and peristalsis in the small intestine will be necessary, but we shall be able to look on these processes from a new point of view after considering the intrinsic nervous control in the large intestine and the stomach.

The Large Intestine.—The same region in the colon may manifest both peristalsis and antiperistalsis. In my observations,[24] and in those of Elliott and Barclay-Smith,[25] antiperistalsis was seen in the middle and distal thirds of the large intestine, from which regions the contents are normally driven by peristalsis. The English investigators have reported further that in the rat the proximal colon, which is commonly worked over by antiperistaltic waves, exhibits the peristaltic reflex if the material it receives, instead of being soft and moist, is stiff and dry.

Since the antiperistaltic waves are not affected by large doses of nicotine,[26] they are like the rhythmic segmenting movements of the small intestine. And again like the segmenting movements, these waves not only utilize the same muscles as the downward-moving constrictions, but, if we may transfer Magnus's evidence to this final region, they probably utilize also the same intrinsic nerve centres that are involved in the local reflex.

The local reflex in the large intestine was first demonstrated by Bayliss and Starling.[27] They found, by using the methods employed in studying the small intestine, that both in the dog and in the rabbit pinching above the recording balloon caused an inhibition of the activities below, and pinching below caused contraction above. The ascending excitation in the dog and the descending inhibition in the rabbit were more difficult to demonstrate than the reciprocal activities. At most the descending inhibition in the rabbit extended not more than 2 or 3 centimetres below the stimulated spot. In both dog and rabbit the activity of the local mechanism diminished from the ileo-colic valve to the anus, thus throwing the evacuation of the distal colon more and more into the control of extrinsic nerves. The local reflex in the rabbit's colon Langley and Magnus were able to demonstrate after degeneration of the post-ganglionic sympathetic fibres.[28] That the cat's colon also is the seat of the co-ordinated reflex was shown by Elliott and Barclay-Smith, who found that distension in the middle third of the large intestine

of this animal causes constriction above the distended area, and relaxation below.[29]

Thus far I have used the terms " peristalsis " and " antiperistalsis," as if descriptive of the same activity, and merely opposed in direction. The only difference between them that has been suggested is the failure of nicotine to stop antiperistalsis, whereas in the small intestine nicotine at once abolishes peristalsis and the reflex on which that activity rests. Antiperistalsis is peculiar in a number of other ways, however, which clearly distinguish it from the propulsive wave.

The chief peculiarity of antiperistalsis is the absence of a region of inhibition projected before the moving ring of constriction. As a result, these rings continue passing over the proximal colon in a close series, each succeeding constriction never checking or interfering in any way with those already started and progressing before it.

A second and important characteristic of the antiperistaltic waves to which I have called attention[30] is their origin. In my first paper on the movements of the intestine, I reported that these waves were seen starting from the " nearest tonic constriction." [31] Elliott and Barclay-Smith also noted that the waves began at " the anal limit of a distended area," " from the upper limits of a ring of constriction," " from a deep constriction which formed and remained with slight oscillations as a starting-point."[32] Although we reported thus our observations, we did not realize the significance of the tonus ring as the source of antiperistalsis. By producing a tonus ring in the proximal colon, however, by a pinch or by applying a weak solution of barium chloride, I have been able to cause the waves to appear at will. By making the ring at the cæcum, repeated downward-running waves may be set going ; by making a new ring now at the terminus of these waves, reversed waves appear, and meet the downward waves progressively nearer the cæcum until only reversed waves are running. Furthermore, a tonus ring made midway in the proximal colon I have seen giving rise to repeated waves which passed away in both directions.[33] The origin of antiperistalsis, therefore, is the tonus ring.

A third feature of antiperistaltic activity in the colon is its rhythmicity. The waves appear one after another at regular intervals. These rhythmic waves must have a source that is rhythmically active. Careful inspection of the tonus ring shows

that at regular intervals it pulsates. Each pulsation sends away a ring of constriction.

A fourth characteristic of this antiperistalsis is its dependence on a state of tension. If a tube is tied into the colon, and as fluid is introduced a tonus ring is made, antiperistaltic waves are usually started by the ring. If now the fluid is largely withdrawn, the waves cease. Reintroducing the fluid starts them again. The observation that antiperistalsis begins as soon as new food enters the colon from the ileum, and Elliott and Barclay-Smith's method of starting the waves by injecting air or gruel, agree completely with the idea that distension is the condition under which the waves originate.

Mechanical extension has long been known as the most efficient stimulus for bringing smooth muscle into activity. The extension, however, must not be merely the elongation of non-elastic substance. When smooth muscle is flaccid or already much relaxed, extension calls forth no response. Only when shortened and resilient—*i.e.*, in a state of tonus—does the pull evoke contraction.

According to Schultz,[34] smooth muscle, when much contracted, is extended more by a given weight than when less contracted and loaded with the same weight. The tonus ring is a region contracted more than the neighbouring regions. We may assume, therefore, that at the tonus ring the neuromusculature is in a condition especially favourable to extension by any internal pressure, and, further, that it will respond to extension by contraction.

In thus responding to an extending force, the smooth muscle of the colon, like that of the small intestine, is, during the entire period of shortening, relatively refractory to stimulation. It begins again to be subject to the stimulus just after reaching its most contracted state—*i.e.*, when again most extensible. Now, by being extended, it is stimulated, and again responds. In explaining the rhythmic pulsation of the tonus ring in response to a constant pull, therefore, the same factors are involved as in the rhythmic contractions of the small intestine.

The movement of a wave of constriction from the pulsating ring towards the cæcum can best be regarded as another instance of the passage of the state of excitation from an active to a less active region in a simple neuromuscular structure—a phenomenon which v. Uexküll has so frequently observed in the nerve net

of invertebrates that he has based upon it a general law.[35] Thus would be explained the departure of waves from a pulsating ring backwards or forwards, or in both directions simultaneously, as described above. In my experience, this progress of a wave does not occur if the wall expands sharply at the edge of the ring. The wall must taper from the expanded to the narrow region before the pulsations will send off the moving constrictions. It is a corollary from the above discussion of the effect of extension on contraction that the expanded region must itself be in a condition to be extended—*i.e.*, possess some degree of tonus—in order to be in a state to respond. If the gut is quite relaxed, the arousing of antiperistaltic waves from a pulsating ring is usually impossible.

The wave departing from the contracting ring leaves a refractory region behind, and is itself a moving refractory state of the neuromusculature. The only direction in which the wave can make progress, therefore, is away from its origin. As soon as the region of the colon next to the ring has contracted, it begins to relax. Thus between moving rings of constriction are moving regions of relaxation. When the region next the tonus ring is relaxed, it is, of course, again subject to an impulse coming to it from the pulsating ring. What is true of this region is true also of all regions lying beyond. Thus, just as in cardiac contraction the pulsations of the sinus set the pace for the rest of the heart, so here in the colon the pulsations of the tonus ring determine the rate at which waves shall appear.

A tonic constriction is itself refractory to the stimulus that comes to it in the form of a constriction wave. My own observations and those of Elliott and Barclay-Smith on antiperistaltic waves observable between the natural tonic constrictions of the colon illustrate the definite boundary set by the state of tonus. The blocking of the waves started at tonus ring *b* by the nearly relaxed ring *a* (Fig. 32) offers another illustration of the same fact.

The dependence of pulsations on an adjustment between locally increased tonus and the internal pressure is also illustrated in Fig. 32. The colon is filled with fluid ; ring *b*, which is deep, is pulsating and sending forth waves ; ring *a*, which has relaxed, no longer pulsates. The two rings are exposed to approximately the same internal pressure. This is adequate as a stimulus for the deeper ring, but not for the less deep. Under such circum-

stances, I have been able to renew rhythmic activity in the quiet ring merely by increasing the internal pressure. In all probability this is what occurs when new food enters the large intestine from the ileum, and starts a fresh series of antiperistaltic waves. And once started, the waves can be augmented by increase of internal pressure. For example, if they are shallow depressions, they can be made much deeper by a series of slight momentary pressures on the gut, which cause repeated slight distensions of the wall where the waves are passing.

The precise relation between the degree of tonus and the internal pressure, which results in rhythmic contraction, is difficult to define. When a tonus ring is first made, either by a pinch or by applying barium chloride, it is a deep and strong contraction, and shows no evidence of pulsations. Only when it has relaxed to some extent does it begin to beat rhythmically. On the other hand, if the pressure within is sufficiently increased, the waves moving along the gut will disappear, and then can only be seen again when the distension is reduced. Both the tonus and the distending force, therefore, can be too great for rhythmic action.

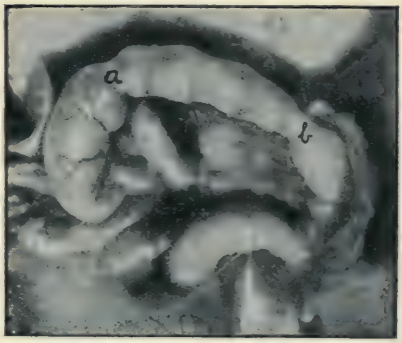

FIG. 32.—PHOTOGRAPH OF A COLON EXPOSED UNDER WARM SALT SOLUTION.

Tonus ring *b* is sending forth antiperistaltic waves, which are stopped by the nearly relaxed tonus ring *a*.

From the foregoing discussion we can understand that, given the state of tonus and a locally increased tonic contraction, antiperistalsis of the colon can be explained. The conditions for the establishment of tonus rings, however, are still undetermined. Since the rings persist after destruction of the spinal cord, they must be maintained by the gut itself. Henderson's observation that the movements of the alimentary canal appear if the carbon dioxide content of the blood is kept normal or increased[36] can be explained as due to the well-known effect of this gas in augmenting myenteric tonus. Probably both the general tonic state of the proximal colon, and also the tonus rings, are of local origin, and possibly directly dependent on the character of the blood-

supply. More than this we are not at present warranted in saying.

Just as we were not able to determine the normal occasion for peristalsis in the small intestine, so likewise we are ignorant of what causes the appearance of peristalsis in the region where antiperistalsis usually prevails. As already stated, change in the nature of the contents may change the direction of the waves. Magnus has found that, when senna is mixed with the food, it causes an evacuation as soon as it enters the colon. He was unable to note the occurrence of antiperistalsis in any of ten animals thus treated.[37] Possibly, as seems to be true in the small intestine, the peristaltic wave of the colon is related to other activities of the region, and is reserved for pushing onward waste material from which all good has been removed or which has dried and hardened, or for quick discharge of irritant and harmful substances. In this activity the mechanism of defæcation is, of course, a distinct aid. This mechanism, however, will be considered in relation to the extrinsic innervation.

The Stomach.—The characteristic activities of the stomach, so long as gastric digestion persists, are the repeated peristaltic waves running over the pyloric end, and the tonic contraction of the cardiac end. The fact that the waves of the stomach, like those of the colon, follow one another in a series indicates that the extensive forerunning inhibition, such as is seen in the dog's small intestine, is absent. Moreover, when nicotine is given, even in large doses, the gastric waves are not stopped.[38] The peristaltic activity of the stomach, therefore, is by this evidence placed in the same class with antiperistalsis of the colon and the segmenting movements of the small intestine.

The first waves of gastric peristalsis are usually seen in the pyloric region; later they begin nearer the cardiac end. This observation proves that there is no special and peculiar region for the origin of the waves. Indeed, I have recently found that by gradually increasing intragastric pressure the waves can be made to start progressively nearer the pylorus; or, as the pressure is decreased, step by step nearer the fundus. Our consideration of rhythmic antiperistalsis in the colon has shown that the waves start at a pulsating ring. In the stomach also the rhythmically recurring waves must have a rhythmically pulsating source. The conditions in the colon indicate further that whether a ring pulsates or not depends on the relation

between the degree of tonus and internal pressure. The same factors I have found operative in the stomach. If the resting organ is contracted, the introduction of fluid at once starts peristaltic waves; if, on the contrary, the organ is flaccid and relaxed, the introduction of material usually has no effect.

During the process of gastric digestion the stomach maintains its contractions with a considerable tonic tightening always existent. The intragastric pressure, 6 to 16 centimetres of water, is a measure of the tonus of the muscle. If while intragastric pressure is being recorded the animal is given adrenalin, the pressure at once falls to zero. Simultaneously peristalsis ceases, and does not begin again until the pressure has to some extent been restored (see Fig. 33).

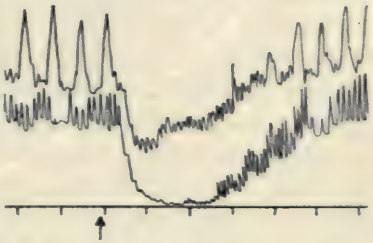

FIG. 33.—RECORDS OF INTRAGASTRIC PRESSURE AND THE CONTRACTIONS OF PYLORIC END OF THE STOMACH AFTER GIVING ADRENALIN.

Peristalsis of the pyloric end (upper curve) begins again after pressure (lower curve) has begun to rise. Time, half-minutes.

The stomach when first filled has roughly a conical shape. The circumference is large at the cardiac end, and progressively smaller as the pylorus is approached. If the contents are fluid or semi-fluid, and are subjected to the tension of the gastric musculature, the pressure throughout the contents (gravity aside) will be uniform. Every unit area of the wall will be supporting the same pressure. Obviously, then, a circumference of given width in the larger cardiac end will be subjected to greater total stress than a circumference of equal width in the smaller pyloric end. Since the forces in the inactive stomach are in equilibrium, however, the circular muscle of the cardiac end necessarily has to exert stronger tension than that in the pyloric end. And, furthermore, since the muscular wall of the cardiac sac is thinner than that of the vestibule, there are fewer muscle fibres in equal cross-sections. The greater circumference and the weaker musculature both tend to place the cardiac region at a disadvantage. The tension of the muscle in this region must therefore determine the pressure in the stomach.

With the conditions of pressure and tonus in the stomach known, how can gastric peristalsis be explained? There is

evidence that the observations already reported on the factors governing activity in the proximal colon can be applied here. As we noted in considering antiperistalsis in the colon, the internal pressure may be too slight to evoke a response in the tonically contracted muscle, or it may be too great. On the basis of these observations, we may assume that at first the muscles of the cardiac end are too much distended to respond, and that those of the pyloric end are too little distended. Between the large cardiac end and the small pyloric end, however, the relations of internal pressure and tonus will be intermediate. At some point the relations will be such that the neuromusculature responds by contraction. The material displaced by this contraction is probably accommodated in the cardiac region where the weakest muscles are working against greatest obstacles. As the contracted circumference relaxes, however, the tonic pressure from the cardiac end again stretches the ring. Thus the contraction will be repeated rhythmically at this point, for the same reasons that were given for the rhythmic response of the small intestine and the colon.

Each pulsation will send off a wave, just as in the colon, but this wave will travel only towards the pylorus. This direction is not taken because antiperistaltic waves cannot occur. If a frog's stomach is distended with water, tied at the two ends, and removed from the body, peristaltic or antiperistaltic waves will run over it, according to the end having a pulsating tonus ring. Similarly in the cat : a tonus ring made near the pylorus will send waves backward over the vestibule.*[39] The failure of peristalsis to move from the pulsating ring in the stomach backwards over the cardiac sac is due to the sac meeting too much pressure to be able to respond. If it were not so, it would itself be the pulsating region. The sac therefore exerts only a tonic grasp on its contents, and the waves move only towards the pylorus. Probably the greater internal pressure in the vestibule which results from peristalsis is a factor in bringing this region, where the muscle rings are small and the muscles themselves are strong, into more powerful activity.

In harmony with the preceding argument is the observation already mentioned, that, when peristaltic waves are running on

* I have never seen these reverse waves traverse the conically-shaped mid-region, though reversal over the more tubular mid-region of man has been reported in clinical cases (Rautenberg, *Deutsches Arch. f. klin. Med.*, 1903, lxxvii., p. 308).

the stomach, their place of origin can be shifted close to the vestibule by increasing internal pressure, or almost to the fundus by decreasing that pressure. In the first procedure the overstretched region is extended, and the pulsating circumference, having to meet a greater distending force, is moved to a region where the muscles are stronger and in a smaller ring. In the second procedure precisely the opposite occurs—the muscles of the cardiac end, gradually less stretched beyond their responding power, begin to contract, and in consequence the pulsatile source of the waves is moved farther towards the area of weakest musculature and largest circumference.

In the stomach, as in the colon, a local neuromuscular mechanism is present for causing a contraction above the stimulated region. Evidence for this conclusion I presented in 1907,[40] and by use of chemical instead of mechanical stimulation Sick has obtained results leading to the same conclusion.[41] Inhibition below the stimulated point is either very slight or extends only a short distance. The local reflex may assure the origin of gastric waves as near the cardia as possible. But that it probably has little effect in the management of gastric peristalsis I have shown by cutting rings through both muscular coats to the submucous connective tissue, thus entirely severing Auerbach's plexus. In one instance six rings were thus cut between the cardiac end of the stomach and the pylorus, and after three weeks the waves were seen passing with perfect regularity, much as in a normal stomach. When a wave approached in an upper section, it stretched the muscles in the next lower section, and they responded by contracting. The contraction passed on rather than back, because the neuromusculature above, still in the active phase, was refractory,[42] whereas that below, relaxed, was ready for contraction in response to extension.

As the stomach empties, the mid-region becomes narrow (see p. 49). The waves then originate at the upper end of this gastric tube at a tonus ring separating the tube from the cardiac sac. The ring forms a depression which has been repeatedly noted in X-ray photographs of the human stomach,[43] and is observable also in the exposed stomach of lower animals. X-ray workers have called this persistent constriction the "incisura cardiaca." The activity of the deepened ring can best be understood in terms of the activity of tonus rings in the large intestine. Since the stomach when full has a conical shape, the

formation of a gastric tube of fairly uniform diameter requires a greater contraction at the cardiac end than at the pyloric end. Because the cardiac incisure, at the extreme cardiac end of the tube, is therefore more contracted than any other part of the stomach, it, like the tonus ring in the colon, is probably more easily distended than any other part. Distension by the internal pressure causes the ring to respond rhythmically. Each contraction sends off a wave towards the pylorus. And as the food is forced on into the intestine the cardiac sac, by tonically pressing on its contents, provides more material for the waves, while helping to maintain the internal pressure necessary for the continuance of gastric peristalsis. Only after the means of exercising internal pressure—*i.e.*, the contents—have disappeared does the peristalsis normally cease.

The origin of tonus in the gastric neuromusculature we shall consider in connection with the extrinsic innervation of the stomach. The continuance of the tonic state, when once established, can be seen in the excised stomach. I have tied the digesting stomach at the two ends, removed it from the body, placed it in warm oxygenated Ringer's solution, introduced a glass tube which rose above the gastric level, and observed for a half-hour peristaltic waves passing over the organ, and the contents being gradually discharged as the volume diminished. Possibly the slow decrease in size (increase in tonic contraction), especially where the pulsations occur, is due to the " contraction remainder " of smooth muscle. This phenomenon, to which Schultz has called special attention,[44] is due to the failure of the muscle to relax fully before the occurrence of another contraction. Evidently, if such a remainder were left as a heritage to each successive shortening, a process of building up would occur. The muscles would become more and more contracted—*i.e.*, the circumference of the stomach would be slowly diminished. The possibility (see p. 60) that the smaller size of the stomach is the result of the muscle fibres slipping by one another, and rearranging themselves in an increased number of layers, should also be kept in mind. For the present we must, therefore, accept the facts of the tonic state, though we are unable to define exactly its nature.

The Myenteric Reflex.—We have now reviewed the activities of the stomach and intestines in relation to their intrinsic nervous control. Each of these regions, and the œsophagus as well,[45]

possesses an intrinsic arrangement whereby a stimulus causes a contraction above and a relaxation below. The relaxation below may be extensive and marked, as in the small intestine of the dog, or may be close and slight, as in the small and large intestine of the rabbit, and in the stomach and œsophagus. We have seen that throughout the alimentary canal the smooth muscle is disposed in an outer longitudinal and an inner circular coat, with Auerbach's plexus between. In the new nomenclature this nerve net is called the "myenteric plexus." Since the local reflex, which acts, as we have seen, in the cardiac and pyloric sphincters, and everywhere else in the wall of the canal to assure orderly progression of the contents, is mediated by the myenteric plexus, I have suggested that it be called the "myenteric reflex."[46]

Although more or less extensive inhibition below a stimulated point is characteristic of the myenteric reflex in the small intestine, abolishment of this inhibition by nicotine does not stop the passage of rings of constriction along the gut. Such rings or "waves of constriction" were described by Bayliss and Starling as moving in either direction regularly and powerfully along the intestine after the administration of nicotine had destroyed the local reflex. The usual source of the rhythmic waves in the dog, they found, was in a slight persistent "ring of constriction" immediately above the dilating balloon.[47]

The conditions in the small intestine appear to be true also of other parts of the canal. Although the myenteric reflex is present and capable of taking control of the musculature, yet it is not always in control. It does not govern the rhythmic contractions of the small intestine, the rhythmic peristalsis and antiperistalsis of the colon, and probably not the rhythmic waves of the stomach. In each of these cases there is no extensive forerunning inhibition. The source of the moving waves is a pulsating tonus ring, and from this ring waves can pass off in either direction. For these activities the tonic contraction of the wall of the canal is all-important.

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CHAPTER XV

THE EXTRINSIC INNERVATION OF THE GASTRO-INTESTINAL TRACT

The stomach and intestines receive their extrinsic innervation from three regions of the central nervous system—from the bulb, from the sacral cord, and from the thoracico-lumbar origin of the sympathetic. Both the bulbar and the sacral systems of nerves are in general motor. The bulbar system, through the vagi, innervates the canal from the œsophagus to the end of the ileum, diminishing in influence as it descends; the sacral system, starting at the anal end, reaches upwards along the colon, with diminishing influence as it ascends. Opposed to these two motor systems is the sympathetic, distributed to the same areas which they innervate, and acting in the main to inhibit what they stimulate.[1] Through these opposed systems the automatic activities of the gastro-intestinal tract can be modified, not, to be sure, voluntarily, but to an important degree by the general bodily state and by emotional conditions. The way in which the extrinsic nerves produce their effects we shall consider in relation to the different parts of the canal—the stomach, small and large intestine—taken separately.

The Extrinsic Innervation of the Stomach.—Connecting the bulb with the stomach are the two vagus nerves. Only one is required to give the entire surface of the stomach a motor supply. Ducceschi has shown that this fact is not due to the transmission of impulses through the myenteric plexus; for if one of the vagus trunks is cut at the cardia, the corresponding part of the stomach does not respond to vagus stimulation. The capacity of one of the cervical vagi to innervate the whole stomach is, therefore, probably due to the interweaving of fibres from the two nerves in their course down the œsophagus.[2]

The vagus fibres distributed to the heart connect with the

intrinsic nerve cells of that organ, and the connection is readily interrupted by nicotine. Although the endings of the vagus fibres in the stomach have not been traced, probably they do not impinge directly on the smooth muscle, but affect it through nerve cells embedded in the gastric wall. The observation of Bayliss and Starling, that nicotine permanently abolishes the action of vagus impulses on the gut,[3] may be interpreted in this manner. For reasons which we shall consider in discussing the innervation of the colon, Langley is inclined to believe that these outlying nerve cells are not part of the myenteric plexus.[4]

The action of the vagus impulses can be shown by recording alterations of gastric pressure as a result of vagus stimulation. The first effect of moderate stimulation is a lessening of the tonus of the muscle. The cardiac sac markedly relaxes; and although the pyloric waves may continue, they are diminished in amplitude. The inhibitory action may last in some instances during sixty or seventy seconds of stimulation; in other instances it continues only ten or fifteen seconds. The inhibition is followed by an augmentor effect indicated by increased tonus and greater amplitude of the rhythmic waves than normal. This stage in turn is followed by the subsidence of both tonus and waves to the initial state. When a vagus nerve is repeatedly stimulated, however, the tonus increases more permanently after each stimulation, and in some instances may remain continuously high.[5] The bulbar supply, therefore, may have not only an augmentor, but also an inhibitory effect, and the evidence from stimulation indicates that the inhibitory effect appears after a shorter latent period, and has less permanence than the augmentor.

The function of the vagus impulses can be inferred also from the effects of severing the nerves. These effects have been studied in a series of experiments by means of the X rays.[6] The right vagus was severed below the origin of the recurrent laryngeal branch, and in a second operation the left nerve was severed in the neck. When both nerves were thus sectioned, the first effect was often total suppression of peristalsis. In two instances in which the second vagus was cut immediately after the animals had voluntarily eaten boiled lean beef, no gastric peristalsis was observed for four hours; and in another instance in which this operation was done the day previous, no gastric peristalsis was seen during the first three hours after feeding. This depression of function was observed also when the splanchnic nerves had

been previously severed. In every instance of vagus section, however, the peristaltic waves, even when restored and running with normal rhythm, were characterized at first by being extraordinarily shallow. Sometimes they were hardly visible; at other times they could be seen distinctly only on the vestibule. But the period during which the movements of the stomach were late in commencing and were notably weak did not long continue. As days passed, these abnormalities largely disappeared, and the waves started at the usual time and had much of their normal vigour.

The similarity between the effects of vagus section on the stomach and on the œsophagus is noteworthy. As we have learned (see p. 28), the immediate effect on the œsophagus of severing the vagi is paralysis. The food stagnates in the tube for hours, distending its walls, but the toneless structures make no response. In time the part composed of smooth muscle recovers its power. Then distension, it will be recalled, becomes the efficient stimulus. At first, however, a slender mass has no effect; the addition of a second mass is required to call forth a constriction. As time goes on, however, even a slender mass becomes effective. The neuromusculature has recovered by itself the state which the vagi formerly maintained—the tonic state which makes it resilient when stretched.

That the restoration observed in the œsophagus is duplicated in the stomach is shown by what occurs when all extrinsic nerves are cut. The stomach develops in itself a remarkable degree of tonus. As I pointed out in 1906, the diameter of the organ in the cat may under these circumstances be only 1·5 or 2 centimetres—a smallness of size almost incredible.[7]

We are now in a position to consider the normal function of the vagus nerves with reference to the musculature of the stomach. We have seen that repeated stimulation of these nerves causes an increased and more permanent tonic contraction of the gastric wall, and that as the tonus increases the peristaltic constrictions increase, and *vice versa*. We have seen also that when the nerves are cut the activities are for some time in abeyance, and even when peristalsis reappears the constrictions at first are shallow. We may conclude, therefore, that the function of the vagi is that of setting the muscles in a tonic state, of making them exert a tension, so that in relation to the gastric contents they are as if stretched by those contents.

The prime importance of the tonic state for normal functioning of the gastric neuromusculature has already been emphasized in the discussion of intrinsic innervation. The evidence there adduced is strengthened by the observation that, when all extrinsic nerves are cut, the œsophagus and the stomach develop in themselves a tonic state. Whether the extrinsic nerves are present or not, the muscles of the gastric wall must be in tonus, and must be placed in tension by the contents before response will occur. In all probability the extrinsic nerves (the vagi) adapt the size of the organ to the varying amount of food taken in. Thus, if the stomach were relaxed, these nerves might set the muscles into tension about a small amount of food which otherwise would not produce any tension whatever. After these nerves are severed, however, the intrinsic tonus which appears compensates by rendering the stomach so contracted that, even if only a small amount is swallowed, the muscles are stretched, and peristaltic activities are at once started.

The question now arises as to the stage in the digestive process at which the vagus influences affect gastric tonus. That during the mastication and ingestion of food impulses pass down these nerves to the stomach was proved by Pawlow's observations on the psychic secretion of the gastric juice.[8] As already stated, repeated stimulation of the vagi results in an increased tonic state, which is much more persistent than that which follows single stimulation. Since a tonic state is necessary for gastric peristalsis, and since peristalsis does not appear if the vagi are cut shortly before the ingestion of food, the inference is suggested that just as there is psychic secretion, so likewise there is psychic tonus. At present, however, no direct evidence has been secured for this inference.

After digestion is well started, the vagus nerves can be severed without altering either the nature of gastric peristalsis or the rate at which the stomach empties itself. This statement is supported both by observations with the X rays, and by inspection and records of intragastric pressure when the digesting stomach was exposed under salt solution. Psychic tonus, like psychic secretion, would be aroused while food was being ingested, and might continue for a period of some minutes thereafter. Then the tonic state must be continued by other agencies. As the above evidence and also observations on the excised stomach show (see p. 194), the tonic state, once established at the be-

ginning of gastric digestion, is self-supporting, and, again like the psychic secretion, maintains itself by some local mechanism.

The inhibitory impulses along the vagi have their function after gastric tonus has developed a considerable pressure in the stomach. By introducing a balloon into the cardiac end of the stomach through an œsophagotomy opening in the neck, the alterations of intragastric pressure and volume can be recorded. If now the animal swallows, the food does not pass down the œsophagus, but emerges through the upper opening. Using this method, C. W. Lieb and I have shown[9] that after each separate swallow intragastric pressure drops almost to zero; and if the balloon pressure is 3 or 4 centimetres of water, the volume of the stomach may increase by 8 or 10 c.c. The fall of pressure begins between two and five seconds after the larynx rises, and the greatest volume change is reached between six and ten seconds after the bolus leaves the mouth. The admirable character of this receptive relaxation of the stomach can be appreciated if we recall that the time required for a bolus to be carried through the cat's œsophagus varies between seven and ten seconds. Thus, whenever a tonic state of the gastric musculature has raised intragastric pressure, an automatic mechanism exists for lowering that pressure while the œsophagus is pushing new food into the stomach. If the vagi are cut, the phenomenon does not occur.*

Stimulation of the splanchnic nerves, most observers have reported, causes diminished tonus of the gastric musculature and weakening of the rhythmic contractions. Again we note the concomitant variation of tonus and rhythmic response to tension. A maximum loss of tone and total disappearance of pulsations and peristalsis occur when adrenalin is administered (see Fig. 33, p. 191). The presence and action of inhibitory sympathetic nerves[10] was thus demonstrated by Elliott. That these nerves exert a constant influence is made probable by the observation that, when all extrinsic nerves to the stomach are cut, gastric peristalsis and the rate at which the stomach empties are more nearly normal than when the vagi alone are cut, and the splanchnics left intact. The abnormality of functioning after vagus

* The recent observation by Joseph and Meltzer (*Am. J. Physiol.*, 1911, xxvii., p. xxxi), that in the rabbit contraction of the pyloric portion of the stomach is accompanied by inhibition of duodenal contractions, may be a phenomenon similar to the receptive relaxation of the stomach. The mechanism of the duodenal inhibition has not been reported.

section, therefore, is due, not only to the absence of vagus impulses, but also in part to the depressive effect of the splanchnics.[11]

Whether sensory impressions arise in the stomach itself is still in question. From clinical experience, surgeons have reported that the stomach, and the intestine also, can be cut, crushed, or burned, in operations on the conscious human subject without any experience of discomfort. According to Lennander's studies, no sensations of pain, touch, heat, or cold, arise in the viscera of the abdomen which are innervated only by the vagi and the sympathetic nerves. This is true either in normal conditions or during inflammation. The pain not infrequently referred to the abdomen is explained as the result of disturbances in the serous membrane and the subserous connective tissue of the abdominal wall, which are innervated by the phrenic, the lower six intercostal, the lumbar and sacral nerves. This parietal surface, like the cornea, seems, when stimulated, to originate only sensations of pain. It may be stimulated by rubbing, especially when inflamed, or by stretching any mesenteric attachment or pathological adhesion between the viscera and the abdominal wall.[12]

In support of the contention that the abdominal viscera are not sensitive to heat and cold, Hertz, Cook, and Schlesinger, have reported that if care is taken to introduce hot or cold water into the stomach through the inner of two tubes, no temperature sensation is experienced. The temperature sensations usually ascribed to the stomach they attribute to stimulation of the œsophagus; for if the water is introduced when the tubes are withdrawn until slightly above the cardia, the subject can tell whether it is hot or cold. Hydrochloric acid, even 0·5 per cent., poured into a normal empty stomach produces no sensation whatever, but strong alcohol (48 per cent.) injected through a gastric fistula causes a burning sensation. Conceivably, however, the alcohol is in part regurgitated into the œsophagus.[13]

The distressing effect of a foreign object in the stomach, such as a thermometer-tube or a balloon, has been recorded by Beaumont and by Moritz (see p. 52). The two conditions most commonly associated with gastric pain are ulceration and cramp. Observations on patients with gastric ulcer have shown that even weak acid introduced into the stomach causes pain.[14] The pain from ulcer in the stomach or intestine is explained by Lennander as a result of inflammation of the lymphatic vessels

and glands which drain the affected region. The painful cramp is attributed to a strong contraction of a part of the alimentary canal which stretches the parietal serosa either directly or through mesenteric connections. In man the duodenum and the colon, because of their relations to the abdominal wall, are especially capable of causing pain, both by inflammations and by powerful contractions.[15]

The clinical evidence of the insensitivity of the viscera has been criticized by Kast and Meltzer. Experimental observations on dogs and cats indicated to them that the operation of opening the abdominal cavity may have an inhibitory effect on sensory impulses, especially in states of bodily weakness. Unmistakable signs of pain can be evoked, they declare, if after a small opening is made in the body wall a short loop of intestine is withdrawn and immediately investigated. In their experience, inflammation increases the irritability.[16] According to Ducceschi, stimulation of the gastric wall with thermal, mechanical, or chemical agencies causes characteristic changes in the rhythm and frequency of respiration, like those attending stimulation of sensory nerves. These effects are produced by way of either the vagus or splanchnic paths. The afferent fibres of the vagi, like the efferent, are distributed from each nerve trunk at the cardia to only one side of the stomach, whereas the fibres in one cervical vagus are sent to all parts of the organ. Likewise the afferent fibres in each splanchnic nerve are connected through filaments from the cœliac plexus with the entire surface of the stomach. Thus only one cervical vagus or one splanchnic nerve would be necessary to carry afferent impulses from any part of the gastric wall to the central nervous system.[17] These observations on the sensitivity of the gastro-intestinal canal, quite apart from irritation of the abdominal wall, have been corroborated by Ritter,[18] whose results correspond to those obtained by Kast and Meltzer. More recently Miller has shown that irritation of the gastric mucosa with mustard evokes salivation, rapid respiration, and the vomiting reflex. All these effects are absent if the vagi have been previously cut. He was unable to demonstrate that the splanchnics transmit sensory impulses of any kind from the gastric mucosa.[19]

From the above brief review it is clear that important unexplained discrepancies exist among investigators, so that a definite decision as to the immediate origin of pain sensations in

the walls of the stomach and intestines cannot as yet be made. There is no doubt that disturbances in these structures result in sensations of one sort or another. Aches, pains, vague feelings of heaviness, are all experienced in pathological conditions of the tract below the diaphragm. The question is as to the possibility of these conditions affecting the central nervous system immediately and not by way of spinal nerves.*

The Extrinsic Innervation of the Small Intestine.—Most observers have attributed to the vagus nerves motor effects on the small intestine. After section of the splanchnic nerves and interruption of inhibitory impulses to the heart, Bayliss and Starling found that repeated stimulation of the vagus in the neck gave consistent results. A very brief inhibitory phase was followed by a rise of tonus and a gradual increase of the rhythmic contractions to an extent above the normal, and, as soon as the stimulation was stopped, by an immediate and considerable increase of tonus and augmentation of the beat. The return to the original state is slow and gradual. The vagus nerves appear, therefore, to convey both motor and inhibitory fibres to the small intestine, although the inhibitory effect is conceivably due to the direct nervous stimulation of a region above the recording ring.[20]

The splanchnic nerves were shown by Pflüger many years ago to have an inhibitory influence on the movements of the intestine.[21] Although other investigators have since described motor effects from stimulation of sympathetic fibres, and still others have believed that the effects are opposite on the longitudinal

* Among the sensations referred rather indefinitely to the abdomen is that of hunger. Either directly or through an effect on the parietal peritoneum gastric conditions may give rise to this sensation. In studying auscultation of the abdominal sounds I had occasion to note repeatedly that the sensation of hunger was not continuous, but recurrent, and that its disappearance was commonly associated with a rather loud gurgling sound as heard through the stethoscope. Since then I have paid occasional attention to the matter, and have experienced disappearance of the sensation as gas was gurgling upward through the cardia. That the gas was rising rather than being forced downward was shown by its regurgitation immediately after the sound was heard. As a suggestion I venture to state that hunger is due to contraction of the nearly empty stomach. The contracted stomach in fasting animals has been noted (His, *Arch. f. Anat.*, 1903, p. 345). In the cat, after forty-eight hours of fasting, the organ may be so small as to look like a slightly enlarged duodenum (Wolff, Dissertation, Giessen, 1902, p. 9). Of course, the hungry stomach, thus contracted, is ready at once to begin rhythmic pulsations on being stretched by food. In this connection it is of interest to note that the disagreeable sensation of hunger, in my experience, is momentarily abolished a few seconds after swallowing, a result which can be explained as due to the inhibition of gastric contraction by vagus influences, in the manner above described.

and circular muscle, the careful work of Bayliss and Starling has demonstrated only inhibition of activity in each muscular layer.

Since the splanchnic nerves bear vasoconstrictor impulses to the bloodvessels of the intestines, and since the primary result of anæmia is cessation of intestinal activity, the inhibitory effect these nerves produce might be due to a diminished blood-supply. This interpretation of the results of sympathetic impulses Bayliss and Starling were able to exclude by causing the usual effects immediately after the death of the animal, when the circulation was no longer present.[22]

The normal functions of the two sets of nerves seem to be exercised continuously. After complete severance of the splanchnic nerves, for example, I found that the rate of passage of lean beef through the small intestine was much accelerated, whereas after total vagus section the passage was slower than normal.[23] Probably the vagus nerves act on the intestine, just as they act on the stomach, to produce a tonic condition of the neuromusculature. Magnus has reported that it is advisable, in studying isolated pieces of the intestine, to take them from a normally fed animal, since the intestine of a fasting animal is less active. If, however, the animal has been without food for three days, the intestine begins activity as soon as placed in Ringer's solution. The condition in the last instance seems not unrelated to the readiness for activity in the highly tonic fasting stomach.

The Extrinsic Innervation of the Large Intestine.—Whether vagus fibres reach the large intestine is still in doubt. Bayliss and Starling were unable to demonstrate that vagus stimulation affected any part of the large intestine.[24] On the other hand, Meltzer and Auer observed that vagus stimulation caused strong contraction of the cæcum in the rabbit.[25] Apart from this possible vagus innervation, the large intestine receives, as already stated, a motor supply through the sacral visceral nerves, and an inhibitory supply from the lumbar cord through the sympathetic system by way of the inferior mesenteric ganglion. The sacral nerves (from sacral roots ii. and iii., and occasionally i., in the cat) do not pass directly from the spinal cord to the colon, but end in ganglia at the side of the rectum and the neck of the bladder. After nicotine has abolished conduction through these ganglia, stimulation of the post-ganglionic fibres still causes contraction. There exist, consequently, in relation to the colon,

peripheral neurons of the motor path which are quite distinct from the myenteric plexus.[26]

Although results have been reported indicating a "crossed innervation" of the two muscular coats—*i.e.*, contraction or inhibition of the circular coat by impulses that simultaneously inhibit or contract the longitudinal coat[27]—Bayliss and Starling in their careful observations found that sympathetic stimulation caused pure inhibition, while sacral stimulation after a momentary inhibition called forth contraction of both the circular and longitudinal coats.[28] These observations Elliott and Barclay-Smith have confirmed, but they found that the pelvic nerves are distributed only to that part of the colon which is involved in the act of defæcation. For example, these nerves supply all but the cæcum in the dog, and the distal two-thirds of the colon in the cat. The region where antiperistalsis prevails does not, therefore, receive motor impulses. Stimulation of the pelvic nerves first increases the tonus of the mid-region, whence then antiperistaltic waves may arise; but continued stimulation causes the distal half of the colon to shorten, and thereafter a strong contraction of the circular coat to spread downward in the manner already described for natural evacuation.[29]

The normal functioning of the two sets of nerves is indicated by the results of sectioning, as well as by the results of stimulating them. Severance of the sympathetic fibres supplying the large intestine causes in the cat and the rabbit no lasting disturbance of the motor functions. After removal of the motor impulses, however, by destruction of the spinal cord or by cutting the nerves, the functions of the colon in the rat and the rabbit are evidently disturbed. Fæces accumulate, and the contractions of the gut are sluggish and weak.[30] Langley and Anderson's observations on the cat with sacral nerves cut indicate a similar defect of function.[31] These functional defects are not the temporary result of motor nerve section, like the inactivity of the stomach after severance of the vagi, for they were observed in the rat and rabbit six weeks after operation. They may be due in part, however, to the continuance of inhibitory sympathetic impulses acting in the absence of their usual opponents. This suggestion is supported by the observation of Goltz and Ewald, that, although removal of both sets of nerves by destruction of the lumbar and sacral cord results in a diarrhœa lasting several days, yet recovery occurs, and after a few weeks the dog exhibits

normal activity of the colon, with fæces of usual consistency discharged at customary intervals. After defæcation the rectum is found empty.[32]

As already stated, defæcation is a reflex initiated by the presence of fæces in the rectum. The section of sensory roots of the sacral nerves supplying the rectal mucosa causes an abolition of the normal co-ordination.[33]

The Innervation of the Sphincters.—Although the cardiac and pyloric sphincters are affected by local conditions, they are, like the rest of the canal, subject also to the central nervous system. The extrinsic innervation of the cardia has been considered. At the pylorus the usual result of vagus stimulation is contraction,[34] but Langley observed also at times dilatation.[35] According to Openchowski, the same stimulation of the vagus that produces relaxation of the cardia simultaneously produces closure of the pylorus, a co-ordination that is evidently serviceable in vomiting. The splanchnics cause in the rabbit contraction of the pyloric sphincter, and when adrenalin is given the same result is to be seen.[36] In dogs, splanchnic stimulation is said to relax or open a closed pylorus.[37]

The ileo-colic sphincter was unaffected, in Elliott's experience, by vagus stimulation. Its tonic closure is due to impulses from the central nervous system by way of the splanchnics. If these nerves are stimulated, the tonus of the sphincter increases; if they are cut or the spinal cord destroyed, the sphincter becomes toneless and permits material to pass back from the colon.[38]

Both the internal and external anal sphincters are normally in a state of tonic contraction. Although the external sphincter is composed of striated muscle, its connection with extrinsic nerves is not interrupted by curare. Destruction of the spinal cord,[39] or removal of the ganglia between the cord and the viscera,[40] causes a loss of tonus of the sphincters, from which, however, they soon recover. Stimulation of the sympathetic nerves in the cat causes contraction of the internal sphincter, and in the rabbit and dog at times contraction, and at other times relaxation.[41] The sacral nerves, when artificially excited, cause closure of this sphincter in the dog, relaxation in the rabbit, and both effects in the cat.

The diverse results reported as the result of stimulating the sphincters are perhaps due to the artificial character of the excitation. In physiological conditions they co-operate with

other processes; the orderliness of their action then is probably produced through nervous connections. In the case of the cardia, Kronecker and Meltzer showed the manner in which the physiological relaxation is associated with the passage of a bolus into the stomach. Further observations on the sphincters with reference to physiological stimuli will be necessary before the functions of the extrinsic nerves can be clearly defined. Meanwhile the only generalization which has been offered is that of Elliott, who has stated that "If the quiet lodgment of the contents be facilitated by the presence of sympathetic inhibitor nerves to the body of the viscus, there will also be sympathetic motor nerves to the sphincter closing the exit."[42] Thus adrenalin, which stimulates as sympathetic impulses stimulate, causes relaxation of the entire gastro-intestinal tract, except at the pyloric, ileocolic, and internal anal sphincters.

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CHAPTER XVI

DEPRESSIVE NERVOUS INFLUENCES AFFECTING GASTRO-INTESTINAL MOVEMENTS

THUS far our review of the extrinsic innervation of the alimentary canal has shown that two influences are affecting its movements —depressive influences through the sympathetic, and augmentor influences through the bulbar and sacral nerves. It is clear that absence of activity may be due either to a failure of the impulses which establish the necessary tonic state of the musculature, or to the predominance of the impulses which depress. In these relations the phenomena attending a condition of general bodily weakness are of interest.

The Influence of General Asthenia.—When the nervous connections between the alimentary canal and the central nervous system are intact, nothing is more remarkable than the responsiveness of the canal to general asthenia. I have had repeated opportunity to examine the movements of the stomach and intestines in animals suffering from " distemper," with purulent inflammation of the nose and eyes, with soft toneless muscles, and every appearance of debility. Under these circumstances, food will lie in the stomach or intestine all day without the slightest sign of a peristaltic wave affecting it. There is total stoppage of the motor activity of the digestive organs.

The result is quite different when the canal is disconnected from the spinal cord and brain. In such a state the stomach and small intestine have been observed exhibiting their normal activities, although the animal was to the last extremity feeble and toneless.[1]

The absence of activity in states of bodily depression is probably due in greatest measure to the lack of necessary tonus in the gastro-intestinal musculature. The animals manifest no signs

of appetite, and do not eat spontaneously. There is, consequently, no occasion for the establishment of the "psychic tonus" which I have suggested as a resultant of the eager taking of food. It is possible, however, that when all nerves are intact inhibitory influences through the splanchnics may also play a part in maintaining the quiet state, for fairly normal activities have been observed in two cases of asthenia when only splanchnic nerves had been severed and the vagi were still intact.

Post-operative Paralysis.—One of the most distressing instances of inactivity of the bowel is that seen occasionally after surgical operations on the abdomen. From what we have learned of the controlling factors, we should expect that this inactivity might be due either to general causes working through the central nervous system, or to local factors, such as the inefficiency of the myenteric plexus or the muscles subject to it. With the hope of determining the relative importance of the modifiable procedures in surgical operations, F. T. Murphy and I undertook to learn the effects of etherization, and of exposing, cooling, and handling the alimentary canal, on the passage of food from the stomach and through the small intestine.[2]

The effect of etherization was tested by etherizing one half-hour or one hour and a half, and feeding about a half-hour there after 25 c.c. of the standard potato and bismuth subnitrate mixture. By the method already described the aggregate length of the food-masses in the intestine was determined at regular intervals after feeding. The results are shown in Fig. 34. Clearly, anæsthesia alone, compared, for example, with high intestinal operation accompanied by anæsthesia (see p. 126), has relatively slight effect. The initial passage of food from the stomach was delayed and the outgo was slow. The passage through the small intestine was also slow. Material reached the colon, not after two or three hours, as in normal conditions, but only after four, five, and six hours. But etherization, nevertheless, did not cause inactivity of the canal.

The effect of exposure was tested by displaying the stomach and small intestine as much as possible without manipulation, during a half-hour's anæsthesia. The visible serosa became dry and lustreless. At the end of the half-hour the abdomen was closed, and when the animal had recovered from the ether the standard food was fed. Fig. 35 represents graphically the

differences between the normal condition and that following exposure. As long ago as 1872 v. Braam Houckgeest[3] noted the disturbing effect of exposure on the action of the intestines,

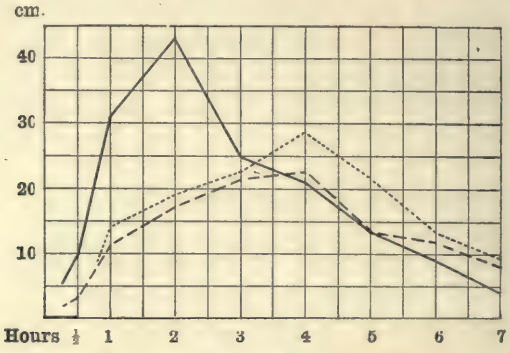

FIG. 34.

The continuous line represents the normal condition; the dash-line the typical condition after etherization for a half-hour; and the dot-line the typical condition after etherization for an hour and a half.

and to avoid it he devised the warm saline bath as the medium in which to retain the normal conditions when the abdomen is opened. The inhibitory effect of exposure might be expected to exert a disturbing after-effect. That seems not to be the case.

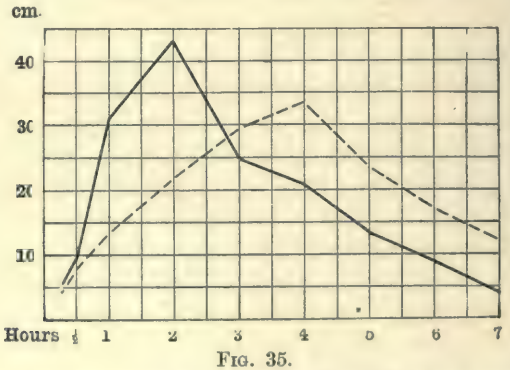

FIG. 35.

The continuous line represents the normal condition; the dash-line the typical condition following etherization, with exposure of the stomach and intestines to the air for a half-hour.

The passage of the food through the canal was hardly different from that which followed etherization alone.

Cooling the body causes a cessation of the movements of the

alimentary canal.[4] It was possible that a temporary cooling of the stomach and intestines, without drying, would stop the movements of these organs. To test this possibility, sterile normal salt solution at 20° C. was poured repeatedly into the opened abdominal cavity for ten minutes during the usual half-hour of etherization. The procedure reduced the body temperature to nearly 33° C. About forty minutes after the abdomen had been closed and the etherization discontinued, the animal was given the standard food. Fig. 36 represents graphically the results. The discharge from the stomach again started somewhat slowly, but the passage through the small intestine was surprisingly rapid. The sharp drop in the curve between the

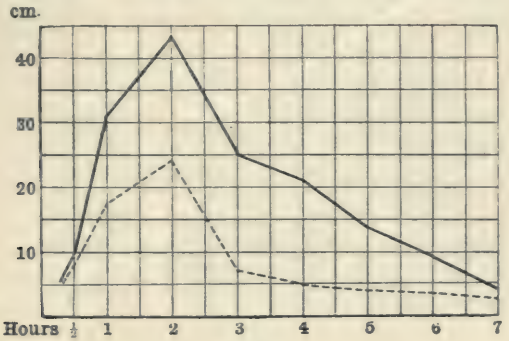

FIG. 36.

The continuous line represents the normal condition ; the dash-line the typical condition after etherization and cooling of the abdominal cavity with sterile normal salt solution at 20° C. The early drop in the dash-line is due to the rapid passage of the food into the large intestine.

second and third hours is thus explained. Although the degree of cooling was excessive, the departure of food from the stomach was about as rapid as when etherization alone disturbed the normal state. And the rapid passage of the food through the small intestine certainly lends no support to the idea that cooling causes enteric paresis.

Handling the stomach and intestines may have different effects according to different degrees of manipulation, and these degrees are difficult to express. In the most severe treatment the organs were stripped between the thumb and first finger with considerable pressure, as would be done in forcing out the contents ; in the less severe treatment the organs were fingered gently in air, or in a trickling stream of warm normal salt solution, with the

parts protected from the fingers by absorbent cotton wet with the solution, or run through the bare fingers within the peritoneal cavity. About an hour after stopping the anæsthetic the animals were fed as in former experiments, and the observations were taken at the usual intervals. The relation of typical cases to the normal condition is shown graphically in Fig. 37. In examining these curves, we should remember that since neither etherization alone, nor such cooling and drying as the viscera in some cases suffered, cause a delay in the passage of food from the stomach, the delay must have been due to the manipulation. Even when the stomach and intestines were handled most gently, either

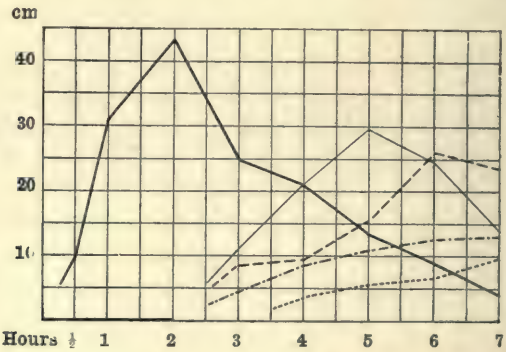

FIG. 37.

The heavy, continuous line represents the normal condition; the light, continuous line the typical condition after handling the stomach and intestine gently under warm normal salt solution; the dash-line the typical condition after handling the organs gently in the peritoneal cavity; the dash-and-dot line after handling them gently in the air; and the dot-line after handling them severely in the air.

under warm normal salt solution or within the peritoneal cavity, no movements of the stomach were seen, and no discharge into the intestine, for three full hours after the feeding. Even after the first departure of food from the stomach the discharge continued very slowly, as shown by the sloping of the curve. The passage through the small intestine was also retarded. In only one case did food appear in the large intestine before the end of the seven hours of observation.

When the organs were removed from the abdomen and handled gently in air, the movement of the food was retarded to a greater degree than when they were fingered in the peritoneal cavity or under warm normal salt solution. So great was the retardation

in one case that not all the food had passed into the large intestine from the ileum twenty-six hours after the feeding. Indeed, the condition then was that reached normally in about five hours.

With rougher treatment in air food was first passed from the stomach only after four hours. Thenceforward it departed very slowly, and, as shown by the permanence of position from observation to observation, was carried through the small intestine with extreme sluggishness. In one case of severe manipulation no food had left the stomach at the end of seven hours, and in another case the food had not yet reached the large intestine twenty-four hours after the feeding (the food used begins to appear there normally at the end of two or three hours). Only a slight amount of food was in the small intestine, and the stomach was still well filled. Manipulation of the stomach and intestine, therefore, even gently and under most favourable circumstances, produced in our experiments much greater effect in the direction of post-operative inactivity than any other of the factors concerned in the manner of operating.

Whether manipulation acted locally on the neuromusculature of the alimentary canal or indirectly through reflex inhibitions from the central nervous system remained to be determined. The observation of Bayliss and Starling that manipulation of the intestine at one point inhibits activities at other points[5] was suggestive of reflex inhibition.

In order to test the source of the post-operative inactivity, Murphy and I undertook a further series of experiments.[6] Evidently, if the inactivity is due to reflex inhibition, handling after the splanchnic nerves are cut ought to have no effect, since the pathway for inhibitory impulses is destroyed. If after severance of the splanchnics, however, manipulation still produces inactivity, the result can be attributed to local disturbance.

Animals in which the splanchnic nerves had been severed aseptically several days before were treated in the same manner as the normal animals on which the earlier observations were made. During the half-hour of etherization the abdomen was opened, and the stomach and intestines, under aseptic precautions, were stripped between the fingers—*i.e.*, roughly handled. Within an hour after etherization ceased the animals were given

the standard food, and observed at the regular intervals after the feeding.

In one animal there was no discharge from the stomach during seven hours of observation, though the next day the stomach was largely empty. Another animal vomited the gastric contents after the first hour. In a third case nothing left the stomach during the first six hours, and then the outgo was slow. In still another instance food began to pass the pylorus at the end of an hour, but the exit was very slow, and at the end of seven hours no food had reached the large intestine. These results correspond closely to the results following manipulation of the stomach and intestines of normal animals. In both there was a marked retardation of the discharge of food from the stomach, and a sluggish condition of the small intestine. The effects of handling, therefore, are not necessarily the consequence of reflex inhibitions from the spinal cord, but can be explained as disturbances of the local mechanisms in the wall of the gut. The observation of Meltzer and Auer that destruction of the spinal cord in the rabbit does not prevent the direct inhibition of peristalsis, observed when the abdomen is opened,[7] and our observation of local inhibition, are in perfect agreement.

Lasting inactivity of the gastro-intestinal tract can also be produced reflexly. Thus Meltzer and Auer found that dissection of the skin over the abdomen produced reflex inhibition of peristalsis, and Murphy and I found that trauma of the testicles during the half-hour of etherization retarded the exit from the stomach for four or five hours, and caused the exit thereafter to be characteristically slow. The movement through the small intestine was likewise very sluggish ; in only one case out of ten did the potato reach the colon within six hours. If the splanchnic nerves have been previously severed, trauma of the testicle has no effect whatever ; indeed, the results observed in these cases compare favourably with those from animals in quite natural conditions.

The animals used in these experiments were vigorous and normal. The trauma to which they were subjected was done under anæsthesia when nervous conduction may be much depressed. The intestine of these animals also may be less sensitive to manipulation than is the human intestine. It is probable, therefore, that if the experimental conditions were superposed on a state of bodily weakness, or were performed

without anæsthesia, or were long continued, as in states of inflammation—thus simulating common conditions in human beings—the results would have been even more pronounced.

From the foregoing evidence it is clear that in any case of adynamic ileus a distinction must be made between the inactivity due to local disturbances in the gastro-intestinal wall and inactivity due to inhibitory impulses from the central nervous system. In any case of unnatural quiescence the first consideration is to determine its source. If the inhibition is extrinsic, any agent that will stop the delivery of inhibitory influences from the spinal cord will permit the stomach and intestines to resume the functions of which they are independently capable. If, on the other hand, the inactivity is the immediate effect of local disturbance, this same agent will have no effect in promoting the restoration of peristalsis. Thus, in our experiments we found that physostigmine salicylate produced a marked, but temporary, increase of peristalsis in cases of reflex inhibition of the alimentary canal, but that tincture of aloes, which is particularly effective in promoting peristalsis in the cat, was quite ineffective after such manipulation of the gut as results in paralysis.[8] The various conditions that affect the alimentary canal locally or reflexly have not yet been experimentally studied, but manifestly on such a study depends the possibility of rational judgment in any particular case.

The Influence of Emotions.—In my earliest observations on the stomach[9] I had difficulty, because in some animals peristalsis was perfectly evident, and in others there was no sign of activity. Several weeks passed before I discovered that this difference in response to the presence of food in the stomach was associated with a difference of sex. The male cats were restive and excited on being fastened to the holder, and under these circumstances gastric peristalsis was absent; the female cats, especially if elderly, submitted with calmness to the restraint, and in them peristaltic waves took their normal course. Once a female with kittens turned from her state of quiet contentment to one of apparent restless anxiety. The movements of the stomach immediately stopped, and only started again after the animal had been petted and had begun to purr. I later found that by covering the cat's mouth and nose with the fingers until a slight distress of breathing occurred the stomach movements could be stopped at will. Thus, in the cat any sign of rage, or distress,

or mere anxiety, was accompanied by a total cessation of the movements of the stomach. I have watched with the X rays the stomach of a male cat for more than an hour, during which time there was not the slightest beginning of peristaltic activity, and yet the only visible indication of excitement in the animal was a continued to-and-fro twitching of the tail.

What is true of the cat has been proved true also of the rabbit, dog, and guinea-pig. Even slight psychic disturbances were accompanied by stoppage of peristalsis.[10] My observations on the rabbit have been confirmed by Auer,[11] who found that the handling of the animal incident to fastening it gently to a holder stopped gastric peristalsis for a variable length of time; and if the animal was startled in any way, or struggled, peristalsis was again abolished. The observations on the dog also have been confirmed. Lommel[12] found that small dogs in strange surroundings might have no movements of the stomach for two or three hours. And whenever the animals showed any indications of being uncomfortable or distressed, the movements were inhibited and the discharge from the stomach checked.

Since the extrinsic innervation of a large part of the intestinal tract is the same as that of the stomach, it is interesting to note the effect of emotional states on the movements of the intestines. Esselmont,[13] in a study of the dog's intestine, noted constantly after signs of emotion a marked increase of activity lasting for only a few moments. Fubini[14] also observed that fear occasioned more rapid peristalsis. The increase of activity in the large intestine during excitement may cause uncontrollable voiding of the gut.[15] There is no doubt that many emotional states are a strong stimulus to peristalsis, but it is equally true that other emotional states inhibit peristalsis. In the cat the same conditions which stop the movements of the stomach stop also the movements of the intestines. A female cat, that ordinarily lies quietly on the holder, and makes no demonstration, will occasionally, with only a little premonitory restlessness, suddenly fly into a rage, lashing her tail from side to side, pulling and jerking with every limb, and biting at everything near her head. During such excitement, and for some moments after the animal becomes pacified again, the movements both of the large and small intestine entirely cease. Such violence of excitement is not necessary to cause the movements to stop. A cat which was restless and continually whining while confined

to the holder showed no signs of intestinal movements during any period of observation (one period lasted more than an hour), although the changes in the distribution of the food observable from one period to the next proved that movements were going on during the quiet intermissions. In another cat, uneasy and fretful for fifty minutes, no activity was seen ; then she became quiet for several minutes, and peristalsis of the small intestine appeared.

When the segmentation process in the small intestine is stopped by excitement, the segments unite and return to the form of a solid strand. In the large intestine antiperistalsis of the proximal portion is abolished by excitement, possibly because the pulsating tonus ring is inhibited.

Since the effects of impulses coming to the alimentary canal along extrinsic nerves have been studied mainly by artificial stimulation, it was of interest to observe the results of physiological stimulation during emotion after different nervous connections had been destroyed.[16] Under these circumstances, such nerves as were left received impulses normally and delivered them normally to the peripheral organ. The conditions, therefore, were highly favourable for determining the course of inhibitory paths. When the vagus nerves were severed, and the splanchnic nerves alone remained, respiratory distress caused the usual total cessation of the movements of the stomach and small intestine. Impulses along the splanchnic nerves, therefore, physiologically inhibit not only the intestines, but the stomach as well. When the splanchnic nerves were cut, and the vagi alone remained, respiratory distress had no effect on the movements of the small intestine ; but when the distress was prolonged until the animal began to toss about, gastric peristaltic waves became very shallow or momentarily stopped. From this evidence it would appear that the inhibitory impulses of the vagi, which are physiologically active after deglutition, are capable of acting also in states of turbulence, although they are not nearly so efficient in stopping gastric peristalsis as are the impulses delivered by the splanchnics. When the splanchnic and vagus nerves are all cut, the movements of the alimentary canal cannot be stopped by respiratory distress. The stoppage in the former cases cannot, therefore, be attributed to any other agency than the nervous influence—as, for example, to asphyxia.

In Pawlow's investigations of the work of the digestive glands,

the importance of pleasurable psychic states for the first secretion of the gastric juice, on which so many processes in the stomach and intestines depend, was strongly emphasized. It is probable, also, as I have indicated, that the initial tonus of the stomach is likewise dependent on the satisfaction of appetite. These results are produced through nervous influences passing down the vagi. The opposing influences, reaching the alimentary canal by way of the sympathetic system during emotional excitement, can totally destroy both the secretory [17] and the motor activities which have been started by the bulbar system. The importance of avoiding so far as possible the states of worry and anxiety, and of not permitting grief and anger and other violent emotions to prevail unduly, is not commonly appreciated, for the subtle alterations wrought by these emotional disturbances are unknown to consciousness, and have become clearly demonstrated solely through physiological studies. Only as the consequences of mental states favourable and unfavourable to normal digestion are better understood can the good results be sought and the bad results avoided, or, if not avoided, regarded and treated with intelligence.

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